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# WASTE MANAGEMENT IMPLICATIONS OF CONCENTRATING SLIMES - EFFECT OF MANAGEMENT PRACTICES

by

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Research report

# WASTE MANAGEMENT IMPLICATIONS OF CONCENTRATING SLIMES


## ABSTRACT

The anticipated increase in demand for sand-size tailings from the uranium industry suggests that the fine-grained or "slime" fraction will require special attention for disposal. The Atomic Energy Control Board (AECB) required information on the behaviour and environmental significance of the fine-grained tailings fraction in disposal facilities. Beak Consultants and Golder Associates were contracted to review the significant characteristics of slimes disposal and prepare a report on the physical and chemical characteristics of fine-grained tailings (Phase 1). This report (Phase 2) presents a summary of disposal and management practices for slimes and outlines potential concerns related to these practices. The report also presents an approach to disposal planning and the implications of available and potential management techniques. Experience with the disposal of uranium slimes is scarce and, therefore, relevant information was borrowed from the other mining sectors to predict the consequences of various disposal scenarios.

## RÉSUMÉ

L'augmentation prévue de la demande de résidus miniers granuleux d'uranium suggère que l'évacuation de la fraction de grains fins ou boues nécessitera une attention particulière. La Commission de contrôle de l'énergie atomique (CCEA) avait besoin de données sur le comportement et les répercussions sur l'environnement de cette fraction de résidus fins dans les installations de dépôt. Beak Consultants Limited et Golder Associates ont été engagés pour passer d'abord en revue les caractéristiques importantes de l'évacuation des boues et pour rédiger ensuite un rapport sur les caractéristiques physiques et chimiques des résidus fins (phase 1). Le présent rapport (phase 2) donne un résumé des pratiques de gestion et d'évacuation des boues et traite de certains problèmes liés à ces pratiques. Il présente aussi une façon de planifier l'évacuation, ainsi que les répercussions des techniques existantes et possibles de gestion. Étant donné le manque d'expérience en matière d'évacuation des boues d'uranium, les renseignements ont été obtenus à partir des autres secteurs miniers pour prévoir les conséquences des différents scénarios d'évacuation.


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## EXECUTIVE SUMMARY

Uranium tailings being discharged at Canadian mines currently consist of a relatively coarse grind with only 50% less than 200 mesh particles. Trends in the mining industry suggest that there will be an increased demand for the sand size fraction to provide support in the older mines when pillars are removed. Sandy tailings backfill may also be utilized in the newer operating mines in Saskatchewan to enhance ore recovery. This shift to backfilling of the sand fraction will result in the need to manage the fine-grained fraction of the tailings (slimes) that are not of practical use for backfilling operations.

The Atomic Energy Control Board (AECB) is responsible for the regulation of uranium tailings management, and is, therefore, concerned about possible environmental effects caused by the concentrations of the fine-grained fractions or slimes. A review-type investigation was contracted out by the AECB to address the implications of concentrating slimes and the impact of disposing these tailings. An initial investigation focused on the characteristics of uranium slimes, with emphasis on the geotechnical and geochemical nature of this material. At the conclusion of that investigation, it was realized that very little information had been compiled on the management of slime-enriched tailings produced specifically by backfilling operations. It was then decided by personnel at the AECB that information was required on the long-term management of slime-enriched tailings, including non-uranium tailings. The purpose of this investigation was to review management options for slime-enriched tailings, with emphasis on techniques and schemes "maximizing the benefits and reducing negative impacts".

This review included an attempt to survey the mining practices in countries other than Canada. A review was also conducted to include other mining and milling operations (non-uranium) in Canada and an extensive search of the literature including the use of a number of computer-based information systems.

Very little firm information was available on the long-term management of slime-enriched tailings. All questionnaire responses provide information for active tailings sites. Tailings operations other than uranium tailings in Canada are generally active, and are not perceived to represent significant potential impacts to the environment. The literature does not appear to contain relevant information to the long-term management of slime-enriched tailings. With this lack of firm database, the remaining report deals

with the issues involved in long-term management of slime-enriched tailings, and a discussion of the positive and negative attributes of these options.

The primary concerns related to the disposal of slime-enriched uranium tailings can be divided into the physical and chemical aspects. Physical concerns are represented by slow consolidation behaviour of the fine-grained tailings and the poor settling qualities of these fines in standing water, especially when the clay content is high. Water control in slime-enriched tailings is a key issue. It plays a role in physical stability of the tailings, the feasibility constraints for discharge and placement methods, and the feasibility constraints on physical containment structures (i.e., dams). Even though the chemical composition of slimes will be somewhat different from the coarse fraction, the chemical behaviour of the fine fraction will not significantly differ from that for whole tailings. Acid generation in pyritic slimes would likely be less significant than that in whole tailings.

The characteristics of the uranium ore and resulting tailings play a role in the choice of management options. Two primary types of ore exist. One is represented by the ore type located in the Elliot Lake area of Ontario, which occurs as a quartz conglomerate, low-grade ore containing low percentage concentrations of pyrite and very little to no clay minerals. The second ore type is represented by that found in northern Saskatchewan in veins usually of moderate to high grade, and containing a high clay mineral content with little or no pyrite or other sulphite minerals that survive the milling process. The characteristics that most severely affect long-term management, therefore, involve the clay mineral content and the pyrite content of the tailings. The positive and negative attributes of slime-enriched uranium tailings management are discussed in the context of these primary tailings characteristics.

It is emphasized here that tailings management should consist of an integrated approach including choices for storage option (primary management scheme) through to post-operational monitoring. The major decisions and phases of slimes tailings management considered here are outlined in Figure 1. This flow diagram shows the phases involved in tailings management and the options and tasks that are involved. The key to such a management scheme involves the planning and major selection processes, not as ad-hoc decisions during operation, but as part of a comprehensive management plan.

Five primary schemes for the management of uranium tailings are addressed. These include underground in worked-out mines, offshore marine placement, deposition in existing lake basins for underwater management, deposition in excavated open pit mines and deposition in surface impoundments. All of these primary schemes have advantages and disadvantages associated with the management of slime-enriched tailings.

Underground placement of slimes has the following disadvantages:

- this method impedes or effectively halts further development in the mine;
- there is a lack of suitable area for decant water to provide the required settling of the fines;
- large volumes of unconsolidated slimes could exceed the capacity of the underground mine works; and
- post-operational monitoring of the subsurface water quality would be complicated by the flow conditions in the fractured rock.

Underground placement has the following advantages:

- no physical containment structures are required;
- the tailings are placed in an environment quite similar to that of the original ore, suggesting similar chemical stability;
- lower water fluxes that are usually associated with deeper systems would enhance the chemical stability of the slimes; and
- this method represents an effective underwater management scheme for pyritic tailings which again enhances chemical stability by reducing or eliminating acid generation.

It is concluded that underground placement of slimes would only be considered when it is known for certain that the mine will no longer be operated. In addition, it is unlikely that slimes could be placed during operation of the existing mine, and that underground placement would actually occur as a post-operational procedure.

Marine offshore placement of slimes has the following disadvantages:

- the physical stability of the slimes deposit would be highly uncertain, especially if the tailings contains a significant clay mineral content;
- even though most marine tailings placement is implicitly passive, monitoring would be required and would probably be quite complex in this environment; and
- if remedial action was required, it would be complicated by the difficult access to the tailings.

Marine offshore placement has the following advantages:

- the marine environment provides very large dilution factors to disperse radionuclides and other contaminants of concern; and
- no physical containment structures would be required.

It is not likely that marine offshore placement of slimes will be important in Canada; firstly, because of the low probability of developing mines in proximity to the coastline and, secondly, because uncertainties are too great with respect to dispersion of contaminants that are associated with uranium tailings. An extensive evaluation of the chemical releases and physical stability concerns would be required before considering marine offshore placement of slimes.

Underwater placement of slimes in lake basins has the following disadvantages:

- this method is limited by availability of suitable lakes in the mining region;
- flocculents or other chemical treatment would likely be required to enhance settling characteristics, especially when the clay mineral content of the tailings is high; and
- there remains some uncertainty with respect to the chemical stability of the slimes and potential leaching characteristics that would affect radionuclide concentrations in the overlying lake.

Underwater placement in lake basins has the following advantages:

- the physical stability of the slimes will be enhanced in the natural sedimentation environment;

- many lakes represent natural groundwater discharge zones, a condition which would reduce the risk of contaminant migration through groundwater pathways;
- the technology for underwater placement is available;
- this environment allows for cover placement to provide further isolation and will likely involve accumulation of natural materials to enhance this situation;
- post-operational monitoring of the slimes would be relatively simple, because of the limited pathways for contaminant migration;
- post-operational physical containment would not be required; and
- this environment has the advantage of underwater management for pyritic tailings to reduce the impact of acid generation.

Overall, the underwater disposal in lake basins provides many advantages when a suitable lake is available. Although some evaluation has already been conducted with respect to chemical releases to the lake after tailings placement, it may be justified to conduct a further evaluation of this potential placement scheme.

Placement of slimes in excavated open pits has the following disadvantages:

- the poor settling characteristics of the slimes would require the use of flocculent or other chemical treatment or, alternatively, an exterior settling pond;
- because underground mining is usually conducted when the open pit operation terminates, there may be water control problems associated with the underground workings due to the excess water that would exist in the pit during slimes placement; and
- monitoring of subsurface water quality would be complicated by flow in the fractured rock environment.

Placement in an excavated open pit has the following advantages:

- the availability of the mined-out pit will usually coincide with the requirement for slimes disposal when backfilling in the underground works is desirable;
- no physical containment structures are required;
- in contrast to underground placement, the location of slimes in the worked-out open pit is usually not restrictive to further mining activities;
- open pit placement of slimes would likely represent underwater management for pyritic tailings if the natural watertable occurs above the final tailings surface;

- o the placement of slimes could be conveniently coupled to the reclamation of the open pit; and
- o open pits usually represent relatively small areas that are amenable to surface reclamation.

Placement of slimes in excavated open pits will be restricted primarily by availability of such structures; however, excavation of pits for disposal of high grade tailings should not be discounted. Experience from the current operation at Rabbit Lake should provide further information on the feasibility of this placement scheme.

The placement of the slimes in surface impoundments has the following disadvantages:

- o physical containment structures are usually required;
- o the slimes are usually not suitable for the construction of the containment structures, and there is a subsequent need for the use of borrow materials;
- o the poor consolidation behaviour of the slimes will require special attention if and when surface remediation is planned;
- o effluent treatment may be required for the control of suspended solids, especially when the tailings contain a high clay mineral content; and
- o exposure of the surface of the tailings to the atmosphere exacerbates the difficulties associated with pyrite oxidation and acid generation in pyritic tailings.

The placement of slimes in surface impoundments poses the following advantages:

- o larger areas are usually available for settling ponds and decant structures;
- o simple discharge techniques are available for this scheme;
- o most of the tailings management experience is associated with surface impoundments; and
- o the lower hydraulic conductivity of the consolidated slimes will reduce the flux of waterborne contaminants through the subsurface.

Surface impoundments are and will probably continue to be the most common scheme for tailings placement. The management of slime-enriched uranium tailings will require water level controls that enhance the physical stability and promote lower watertable levels in the tailings. Surface reclamation will almost certainly be required to reduce

problems with wind erosion and possibly to deal with the acid generation problem in pyritic slimes. Because surface impoundments are most likely to dominate in the management of uranium slimes, the remaining discussion focuses on the relevant management options related to this scheme.

The choice of options used in the operation of the impoundment should also be comprehensive in that many aspects are expected to be interrelated. The planning should be similar to that used to select primary management options. A flow diagram is presented in Figure 2, which outlines the issues and options considered here for managing the surface impoundment of slimes. These issues and options are discussed briefly here.

Potential sites for surface impoundments are limited to natural valleys and shallow lake basins in the Canadian environment. Stack-type impoundments, which comprise physical containment structures on all sides, will not likely be feasible for the management of slimes in the Canadian climate. This is a function of physical stability related to expected water levels within the tailings.

Perimeter settling ponds are the preferred option for slimes impoundments. Perimeter ponds are those that develop downgradient from the discharge area in a depression formed by the natural topography or against a containment structure. Centrally located settling ponds pose certain problems for decommissioning and water management after the tailings operation ceases.

Containment structures that are almost always required for surface impoundments will likely also require the use of borrow materials, because slimes are not appropriate for use in the construction of these structures. The undesirable quality of slimes relates to moisture retention and physical instability.

The poor settling characteristics of the slimes, especially those with high clay mineral content, may require special treatment. Flocculents or polymers may be considered for use to mitigate settling problems in the tailings impoundment. Alternatively, dewatering may be considered using presses or filters when the slimes volumes are not large as might occur when high-grade ores are being processed. Tailings at Collins Bay (Saskatchewan) are now being dewatered. Dewatering will not likely be a practical option when the operation involves very large volumes of tailings.

Discharge methods appropriate for the placement of slime-enriched uranium tailings include conventional end of pipe discharge, sub-aqueous, sub-areal and thickened methods. Conventional discharge (end of pipe) will require large areas and distant settling ponds. It has been demonstrated at other mining operations that natural segregation along the discharge path is not significant with slime-enriched tailings. Sub-aqueous methods of discharge present problems of underwater placement with respect to settling of the solids. Again, large areas would be required. Sub-areal discharge is a preferred method for the placement of slimes that will enhance settling and consolidation, but will require large areas and operator attention for rotating discharge spigots. Modifications to the sub-areal discharge method to take advantage of the high moisture retention capacity of the slimes and the positive effects on acid generation in pyritic tailings is possible. Thickened discharge is an option that has not yet been practiced widely, and may not be very practical for slimes placement. The implications of thickened discharge for slimes are not readily apparent.

Seepage management will depend on the design of the retaining structures and slimes impoundment. If the impoundment is designed to promote drainage of the tailings during the discharge operation, then large quantities of water would be produced at some location outside the impoundment. This would occur, for instance, if finger drains were used in the impoundment. Collector trenches outside of the impoundment have been and could be used to re-route seepage with a potential for recycling of this water.

Site reclamation at surface impoundments will almost certainly involve the use of some type of cover. The purpose of a cover will be to provide dust control, to enhance physical stability possibly by promoting consolidation, to reduce infiltration across the surface of the impoundment, and possibly to provide greater chemical stability by reducing oxidation rates and acid generation. The placement of covers composed of geologic materials will require consideration of significant consolidation that is likely to occur in the slimes over long periods of time. If the use of clay materials for the cover is planned, then almost complete consolidation will be required before cover placement. Other cohesionless materials would be less susceptible to disturbance during consolidation of the slimes. Water covers may not be feasible in surface impoundments because standing water would enhance physical instability. Water covers are best suited to natural depressions such as shallow lakes. A vegetation cover is implicit in almost all reclamation schemes. The high water content and low nutrients expected in the slimes-

enriched uranium tailings suggest that soil or other geologic material covers would be required for vegetation growth.

In conclusion, the three preferred primary management schemes for slimes include:

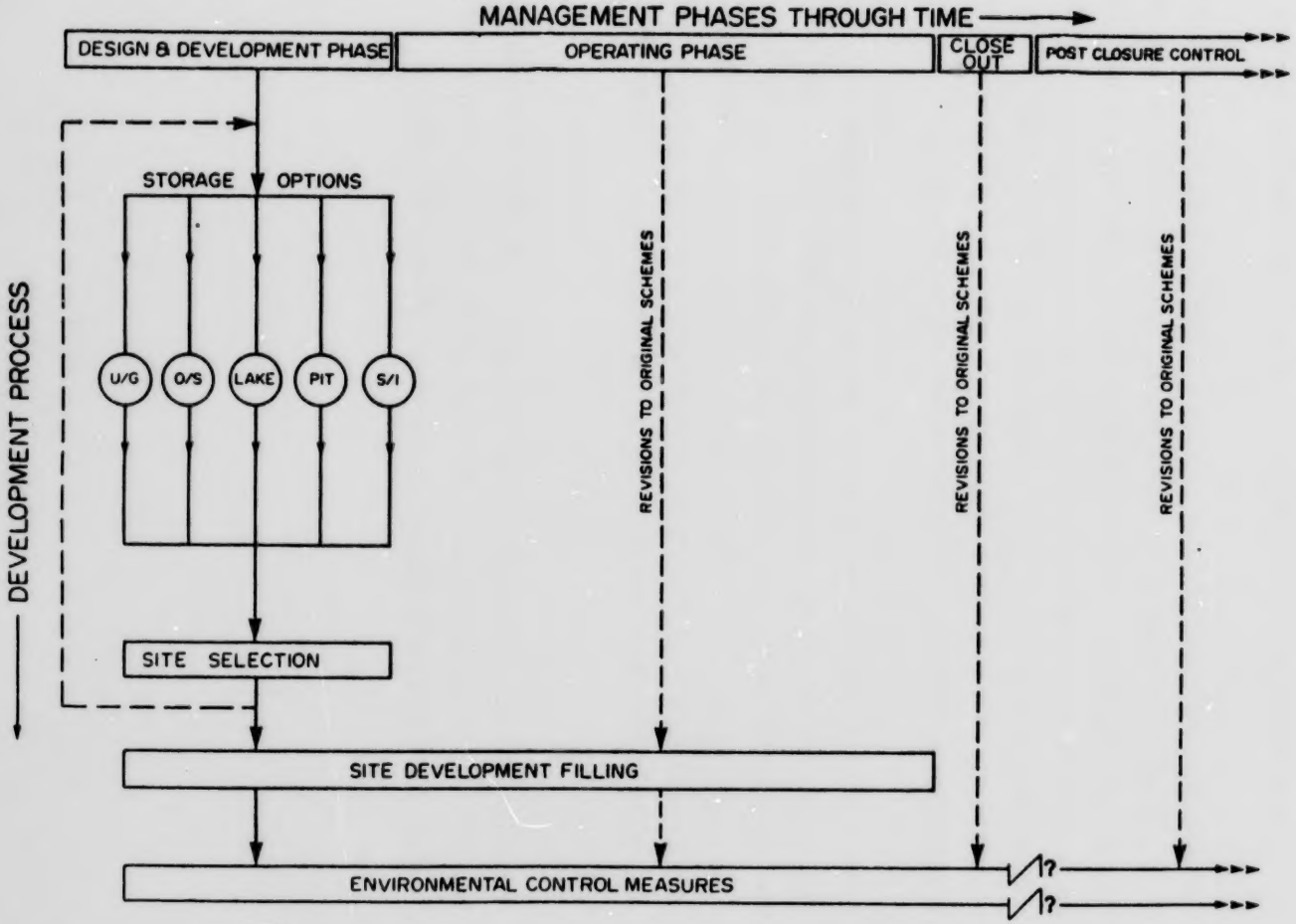
1. excavated open pit filling where available.
2. shallow surface impoundments, and
3. underwater disposal in lake basins where an appropriate site is available.

The primary consideration for almost all disposal schemes will be the settling behaviour of the slimes and long-term consolidation. Settling problems will be reduced most significantly in shallow surface impoundments, with large areas available for the perimeter ponds. Site accessibility will remain problematic to some extent when surface reclamation is required in these impoundments. If the problems of settling can be overcome for the excavated open pits and underwater placement in lake basins, then accessibility to the surface for reclamation may not be important.

A more detailed relative rating of the various primary management schemes is given in Table 1. It sould be noted that underground placement may be preferable in some cases and adequate in others based on tailings behaviour, but may not be adequate in terms of mine management. In contrast, underwater placement in lake basins is promising and may be preferred even though some uncertainties related to long-term behaviour exist. The ratings given here are obviously subject to some overruling factors that could be site-specific.

A similar relative rating for management options in surface impoundments is given in Table 2. This type of rating matrix could aid in the decision-making required to adopt methods for tailings management in the design phase of the facility.

FIGURE 1 Development and Management of a Uranium Slimes Disposal Facility




Legend

| | |
|---|---|
| U/G | underground |
| O/S | offshore marine |
| Lake | underwater lake |
| Pit | excavated open pit |
| S/I | surface impoundment |

FIGURE 2 Development and Management of a Surface Impoundment Facility for Uranium Slimes

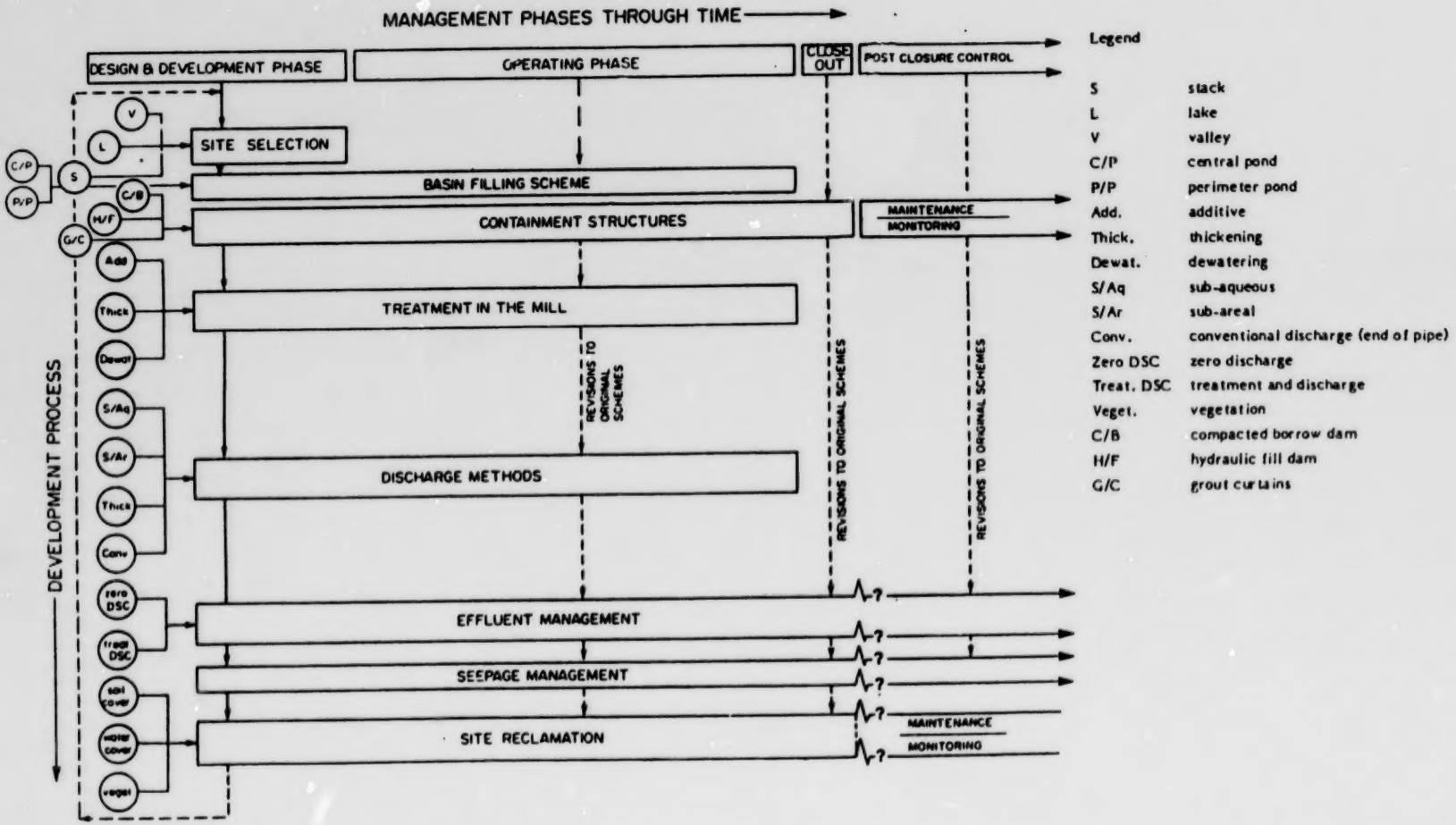


TABLE: 1 SUMMARY APPRAISAL OF STORAGE FACILITY OPTIONS FOR URANIUM SLIMES MANAGEMENT

| HYDROLOGY | SEMI-ARID ENVIRONMENT | | | | SUB-HUMID ENVIRONMENT | | | |
|---|---|---|---|---|---|---|---|---|
| CANADIAN CONDITIONS / TAILINGS CHARACTER | Acid Generating Tailings | | Non-Acid Generating Tailings | | Acid Generating Tailings | | Non-Acid Generating Tailings | |
| DISPOSAL OPTIONS | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals |
| Underground | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Offshore | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Lake Basin | 2 | 2 (1)? | 2 | 2 | 2 | 2 (1)? | 2 | 2 |
| Excavated Pit | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Surface Impoundment | 3 | 3 | 2 | 2 | 3 (2)? | 3 (2)? | 2 | 2 |

NOTES:
1. Slimes Disposal Options are ranked qualitatively in accordance with the system indicated in the Legend. If an option is not available or economically viable, the next option in rank shoud be considered.
2. Long term reliability is a dominant factor in the ranking of the options shown. For further details refer to discussion in report text.

LEGEND

1. - Preferred
2. - Adequate
3. - Doubtful (detailed appraisal required)

TABLE: 2 SUMMARY APPRAISAL OF OPTIONAL MANAGEMENT METHODS FOR URANIUM SLIMES IMPOUNDMENTS

CANADIAN CONDITIONS

OPTIONAL MANAGEMENT METHODS

| HYDROLOGY | | SEMI-ARID ENVIRONMENT | | | | SUB-HUMID ENVIRONMENT | | | |
|---|---|---|---|---|---|---|---|---|---|
| TAILINGS CHARACTER | | Acid Generating Tailings | | Non-Acid Generating Tailings | | Acid Generating Tailings | | Non-Acid Generating Tailings | |
| | | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals |
| Site Selection | Valley | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 |
| | Lake Basin | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Stack | X | X | 3 | 3 | X | X | 3 | 3 |
| Filling Scheme | Central Pond | X | X | 3 | 3 | X | X | X | X |
| | Perimeter Pond | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Containment Structures | Borrow Fill Dam | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Hydraulic Fill Dams | X | X | 3 | 3 | X | X | X | X |
| | Grout Curtains | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 |
| Mill Treatment | Additives | 1 | 1 | 3 | 3 | 1 | 1 | 3 | 3 |
| | Thickening | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Dewatering | X | X | X | X | X | X | X | X |
| Discharge Methods | Subaqueous Discharge | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 3 |
| | Subaerial Discharge | 3 | 3 | 1 | 1 | 3 | 3 | 1 | 1 |
| | Thickened Discharge | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Conventional Disch. | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Effluent Management | Zero Decant | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| | Treat & Discharge | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Site Reclamation | Soil Cover | 3 | 3 | 1 | 1 | 2 | 2 | 1 | 1 |
| | Water Cover | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Vegetation | X | X | 2 | 2 | X | X | 2 | 2 |

NOTES: 1. Management methods are ranked qualitatively in accordance with the system indicated in the Legend. The ranking applies within each given set of "Canadian Conditions" and is not intended be all encompassing.

2. Long term reliability is a dominant factor in the rank of the options shown. For further details refer to discussion in the report text.

LEGEND

1. - Preferred method
2. - Adequate method
3. - Doubtful method (detailed appraisal required)
X. - Not recommended or inadequate

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APPENDIX 1: Annotated Bibliographies for Selected References

APPENDIX 2: Summary of Questionnaire Responses

## 1.0 INTRODUCTION

The proposed use of coarse-grained uranium tailings for backfill in mines as structural support must include consideration of the disposal of the increasingly fine-grained fraction of the tailings. Future uranium mining in Canada is anticipated to involve an increase in pillar recovery in older operations in reef-type orebodies, as well as an expansion of operations in vein-type orebodies. Both trends will result in an increase in backfill mining methods, which will deplete the sand fraction of the "whole" tailings. The sands will become a resource component of the mining plan, while "tailings management" will increasingly involve the management of concentrated slimes fraction.

The Atomic Energy Control Board (AECB) is responsible for the regulation of uranium tailings disposal, and is therefore concerned about possible environmental effects caused by the concentration of the fine-grained fractions or "slimes". The AECB has initiated studies to investigate the implications of concentrating slimes and the impact of disposal of this material on the environment. The first phase of this investigation included a report entitled "Waste Management Implication of Concentrating Slimes. 1. Characteristics and Potential Problems". The second phase of the investigation for which the results are presented in this report address the management options and attempt to deal with the long-term implications for disposal.

The purpose of this investigation was to review current management practices for slimes disposal or proposed methods of management that are viable and select or recommend the most preferred methods in terms of positive environmental attributes for long-term management of slimes disposal. The Phase I report summarizes the characteristics of uranium tailings slimes, and indicates that both negative and positive characteristics exist to impact the surrounding environment. The rationale for reviewing management techniques was, therefore, based on optimization of practices to provide minimal impact to the environment.

All available uranium tailings management experience is based on whole or unsegregated tailings. For this reason, the review of management practices has included other mining operations that involve fine tailings, as well as extrapolation of current methods and practices used for unsegregated uranium tailings.

The scope of this report includes a brief review of underground and underwater management, including marine and lake basins, as well as tailings deposition, excavated pits and surface impoundments. Only open pit and surface impoundments have been used in uranium tailings management to date, with the latter being the more dominant practice. Because surface impoundments are likely to remain the most widely used form of tailings deposition, a more detailed discussion of this aspect of tailings management is given in this report.

The methods used in this investigation include a thorough review of the literature, including computer database search, discussions with appropriate individuals in the mining business, and a questionnaire survey to various mining operators throughout Canada, the U.S., Great Britain and Australia. A list of databases used in the computer search is provided in Table 1.1. The listings for all, but two, of these database searches included abstracts of the pertinent references. In excess of 300 references were screened for relevant information, after which a subset of about 40 references was obtained for further examination. Of these, about 30 were found to contain some useful information. An annotated bibliography of selected references is shown in Appendix 1.

A large number of individuals in the mining sector was contacted by telephone to discuss aspects of slimes disposal and management. Comments by these people have been considered and incorporated into the discussion presented in the report.

A questionnaire was developed in coordination with individuals at the AECB. The information requested included details on current and proposed tailings management schemes with special relevance to slimes management. In excess of 35 questionnaires were distributed in Canada, and a number of others were given to mining companies in Australia, the U.S.A. and Great Britain. A total of eight responses were returned. A summary of responses to this questionnaire survey are presented in Appendix 2.

TABLE 1.1 DATA BASES USED IN COMPUTER LITERATURE SEARCH

1. Georef - 1785 - 1986/Sept.
   (Corp. American Geological Institute)

2. E.I. Engineering Meetings - 86/Aug.
   (Corp. Engineering Info. I.N.C. - 186)

3. Compendex - 70 - 86/Aug.
   (Corp. Engineering Info. Inc. 1986)

4. N.T.I.S. - National Technical Information Service

5. QL Search Service - Mining Technology (CANMET Ottawa)

## 2.0 LONG-TERM MANAGEMENT OBJECTIVES

### 2.1 Introduction

Historically, the term tailings "disposal" has been applied to describe the transport, discharge, treatment and containment of mill wastes. More recently, the safe containment of uranium mill tailings is considered to include long-term active controls, including maintenance and monitoring after tailings discharge ceases. Tailings "management" has, therefore, been adopted to describe the handling of mill tailings.

At present, the concept of tailings disposal has a restricted connotation of safe, permanent containment of tailings, with no requirement for active, long-term maintenance or monitoring and no intention of retrieval. In contrast, tailings management implies the need for long-term monitoring and active controls for the safe containment of the wastes, and is clearly the more appropriate term to use in connection with uranium mill tailings. The uncertain problems associated with long-term chemical and physical stability of uranium tailings implies that institutional control would be required for an indefinite period after site decommissioning.

A primary objective of this report was to evaluate existing and potential tailings management practices in terms of maximizing the benefits and reducing negative impacts for management of fine-grained uranium tailings (slimes).

As part of this evaluation, a world-wide survey of the existing practices and performance of tailings (slimes) management facilities has been attempted. The survey was not restricted to uranium slimes management facilities, because some of the problems encountered with many other mining/milling wastes (e.g., acid generating potential, dissolved metals in the liquid phase of the wastes, presence of clay minerals, etc.) are common to uranium slimes. The response to the survey (questionnaire) unfortunately was poor. The responses are given in Appendix 2, and inferences/conclusions derived from these have been incorporated in the discussions which follow below.

## 2.2 Long-Term Physical Stability

One of the principal objectives of uranium slimes management is to achieve long-term physical stability of the wastes in the environment. There is a high degree of interdependence between the long-term chemical and physical stability of the waste. Uncontrolled releases of the liquid or solid phases of the waste to the environment would expose the tailings to an altered geochemical environment, which could cause an accelerated release of radionuclides, and possibly other contaminants.

The radioactive nature of the wastes is a dominant factor contributing to the need for safe physical containment of these wastes. The failure of a uranium tailings impoundment and consequent dispersion of the tailings in the environment represents a greater potential impact than non-radioactive wastes. Hence, more severe design criteria are generally used in evaluating the physical stability of a uranium tailings disposal facility, than for any other types of tailings.

The physical properties of the slimes themselves are a major determining factor in the long-term physical stability in the environment. These properties have already been presented and discussed in Part 1 of this report. It is recognized that the slimes will be structurally weaker than the traditionally coarser tailings, especially if the clay content is significant, and hence provision of safe containment, covers, etc. must recognize this factor. The finer tailings will also likely be more difficult to deposit and contain safely/permanently in underwater and underground environments. These and other aspects will be discussed in greater detail below, where various methods/practices for the disposal of uranium slimes are evaluated.

## 2.3 Long-Term Chemical Stability

The release of radionuclides and other deleterious constitutents from slimes will result from a number of processes. These include kinetically controlled dissolution of some minerals and solids that occur in the tailings. The dissolution of other minerals will be controlled by thermodynamic equilibrium with the solid phases. Other reactions are possible, including sulphide mineral (pyrite) oxidation which entails reaction with atmospheric oxygen to form products including low pH pore water. The controls on each of these types of reactions are different, and hence the chemical nature of the pore

water in contact with the slimes solids will vary according to the appropriate and most significant controls.

The chemical composition of pore water in slimes deposits was discussed extensively in Part 1 of this report. In summary, it is noted that the pore water that migrates beyond the boundaries of the tailings impoundment either as surface water or groundwater will include a variety of chemical constituents that depend on the original mineralogical composition of the ore as well as any chemicals added in the mill. Chemical additives are specific to the milling operation and ore type, and hence the concern for releases of chemicals at non-uranium mine sites may not be relevant to the uranium mining situation.

In general, it can be stated that two major concerns exist for the long-term chemical stability of uranium mill tailings. First is the amount of water that infiltrates through the tailings and results in leaching of radionuclides and other potentially detrimental chemical constituents. Higher values of water flux through the tailings will normally result in greater releases of these constituents. The second concern is related to the availability of oxygen within pyritic or sulphide tailings in which acid generation may occur. Oxygen flux through the surface of the tailings controls the overall rate of acid generation that may subsequently result in low pH pore water within the tailings. The acidic condition that occurs will effectively enhance the concentrations of many potentially toxic constituents in the pore water, and will increase the rate of release to the environment. The main emphasis for long-term chemical stability, therefore, should be on controlling the flux of water and oxygen into the tailings mass.

In general, it can be stated that slime-enriched tailings will have characteristics which decrease both the rate of infiltration of water and rate of acid generation (oxygen transport) relative to whole tailings. The hydraulic conductivity of consolidated slimes will be much lower than that of whole tailings. This will increase the proportion of surface runoff relative to the amount of infiltration. The fine-grained nature of the slimes will also result in high moisture retention that will inhibit oxygen movement into the tailings. Overall, it would seem that the chemical stability of slimes will be greater than that of whole tailings. The only negative chemical aspect of slimes is the greater proportion of contaminants in the solids compared to whole tailings. For this reason, greater quantities of contaminants are available for release to the environment, even though the rate of release may be slower than that from coarser tailings.

## 3.0 CHARACTERIZATION OF THE CANADIAN SITUATION

### 3.1 Summary of Uranium Tailings Management Practices in Canada

Three basic types of ore have been exploited for uranium in Canada:

- o uraninite mineralization occurring in pegmatites;
- o pitchblende mineralization in quartz-pebble conglomerates (reef-type); and
- o pitchblende and brannerite mineralization as veins that are often associated with an unconformity below the Athabasca formation.

These have been reviewed in Part 1 of this report, and will not be discussed in detail here.

The two major uranium ore types presently mined in Canada are represented by the Elliot Lake variety (congomerate) at the Denison and Quirke Lake operations, and by the Saskatchewan variety (veins) at the Key Lake and Rabbit Lake properties. Although the alkaline milling process has been used in one operation in the past (Beaverlodge), the standard uranium extraction process consists of a sulphuric acid leach with limestone/lime neutralization prior to discharge.

The tailings management practices at the various properties have not been significantly different. Most involve(d) a surface impoundment facility for that fraction of tailings not used as underground backfill (i.e., the major fraction of the total to date). There has been no deliberate attempt to operate these facilities so as to produce submergence or even complete saturation of the tailings. Instead, control of contaminants during operation has been achieved mainly through effluent treatment and provision of "impervious" (low permeability) barriers, where warranted.

Two of these tailings management facilities have been decommissioned relatively recently. These are the Beaverlodge and Faraday mine facilities. The major highlights of each decommissioning plan are outlined below (Knapp, 1986).

The Beaverlodge uranium mine operated on a carbonate leach circuit and produced non-acid generating tailings. The final reclamation plan included:

- o removal of spilled tailings from the Ace Creek Floodplain; other spilled tailings would be covered where possible or left undisturbed if vegetated;
- o removal of tailings and sludges in Mine Water Lake with subsequent disposal in the mine;
- o provision to cover exposed tailings in Fookes and Marie Lake delta areas;
- o removal of Meadow Lake sludges;
- o demolition of the mill and burial in the wasterock pile; and
- o man-made dams at Fookes and Marie Lakes replaced by spillways.

The Faraday Mine operated on an acid leach circuit and produced non-acid generating tailings. The primary reclamation concept was originally to mothball the facility and reclaim the tailings area. This plan was modified when it was realized that there was very little future prospect for reopening the mine. Therefore, the mill buildings have been demolished, the mine sealed and the tailings surface covered with gravel and rock and vegetated.

A detailed discussion of the characteristics of Canadian uranium tailings is given in Part 1 of this report. A summary is given in Section 3.2, below.

### 3.2 Summary of Slimes Characteristics

The composition and characteristics of uranium mill tailings depend on the original ore type and the milling process used. In Canada, the sulphuric acid leach process has been used almost exclusively (with the exception of the Beaverlodge operation) on all ore types. This process requires only a relatively coarse grind, and generally the mill-feed consists of 50% less than 200 mesh (75 micron diameter) particles.

In the past, the leach residues and spent leach solution were generally discharged directly to tailings impoundments after neutralization to pH values of about 7. Later, lime addition raised pH values to between 8 and 11 prior to discharge. Lime treatment also resulted in the formation of many precipitates such as ferric hydroxides and gypsum that were combined and discharged with the solids.

The effect that the separation of sand and slimes prior to discharge may have on the concentration of radionuclides, metals and other contaminants in the solid and liquid phases of the slimes has been discussed in Part 1 of this report. A summary of the characteristics of slimes is given below.

1. The relative concentration of secondary precipitates increases in the slime-enriched fraction. The relative quantity of these precipitates vary with the ore type, but generally comprise 5 to 10% of the total solids in unsegregated tailings from Elliot Lake and up to 25% in Saskatchewan tailings with greater concentrations in the fines. The presence of these secondary solids influence both geochemical and geotechnical properties of the tailings.
2. Softer minerals, such as gypsum, occur in greater percentage in the fine-grained (slimes) fraction of the segregated tailings.
3. Sulphur (as pyrite) and carbonate (as calcite) do not appear in markedly different concentrations in the slimes from those of the unsegregated (whole) tailings.
4. Radium-226 and Pb-210 are radionuclides present in the whole tailings, which are concentrated in the slimes of tailings from Elliot Lake. Tailings from high-grade ores from Saskatchewan (i.e., Key Lake) show much less segregation of these radionuclides. There does not appear to be any evidence for grain-size segregation of other radionuclides.
5. Segregation of metal content by grain size is not well-established for the Elliot Lake ores. However, the high-grade Saskatchewan ores exhibit higher concentrations of metals in the slimes than in the coarse fraction of the tailings.
6. Acidification of pore water is less severe in slimes than in the sand fraction of pyritic tailings because of the lower rates of oxygen transport. Higher moisture retention in the slimes is responsible for this behaviour.

Although there is obviously a large degree of interaction and interdependence between the various geochemical and geotechnical properties of uranium slimes, there are two primary characteristics which generally dominate the geochemical and physical behaviour of the tailings mass. These characteristics are:

- acid generating potential, and
- presence of clay minerals.

Acid generating potential controls, to a large extent, the long-term stability of many metals and some radionuclide contaminants. Oxidation of pyrite that is common to Elliot Lake tailings results in acidification of porewater and release of metals. Specific management considerations will be required to address long-term chemical stability of the acid-generating tailings in the Elliot Lake region.

Certain metasedimentary orebodies of the Saskatchewan region may produce slimes with a significant clay fraction. The high clay content results in poor settling and sedimentation characteristics. In contrast, however, a significant clay content decreases the hydraulic conductivity of the tailings mass. Lower hydraulic conductivities will result in lower rates of pore water movement, and will also likely reduce radon emissions. However, it is probable that special considerations will be required for consolidation of the high clay-content slimes from the tailings in Saskatchewan.

The influence of these major characteristics on slimes management practices will be discussed in greater detail below.

### 3.3 The Role of Climate

Climatic conditions, and precipitation characteristics in particular, are important in two ways. First, the flux of contaminated water discharged from the tailings will depend on the net infiltration rate. Attempts to reduce infiltration will have to address the relatively large amount of precipitation expected over the short periods that include the spring and fall seasons. Second, moisture is important in reducing acid generation in pyritic tailings.

One of the more effective means of ensuring long-term geochemical stability of pyritic uranium tailings is to maintain permanent saturation of pore spaces. Climatic conditions will be important in determining the long-term moisture characteristics of slimes that are located in surface impoundments or excavated pits.

The Canadian climate varies from arid to humid. For instance, Elliot Lake, with an average annual precipitation of 900 mm and average annual evapotranspiration of 200 mm, can be classified as humid. On the other hand, Key Lake, Saskatchewan, with precipitation and evapotranspiration rates of 400 and 300 mm respectively, can be classified as semi-arid.

In the northernmost areas, most of the precipitation occurs in the form of snow. This factor, in conjunction with rapid spring melt conditions, means that, during most of the year, conditions can be described as arid.

There is a significant amount of experience in managing fine-grained gold tailings in South Africa (Grange et al., 1982), where the arid climate contributes to the physical stability of impoundment structures. The impoundment designs used in the Canadian environment must be different than those in South Africa, mainly because of climate and specifically because of the significantly different water budgets.

The "arid" conditions in Canada are, however, not as severe as those in the southwestern United States or South Africa, for example, which are both characterized by high ambient temperatures, low groundwater tables and scarce permanent surface waterbodies. Although net precipitation is low or non-existent in the Canadian north, groundwater tables are relatively shallow, and there is an abundance of permanent surface water in poorly-drained topographic lows (generally bedrock controlled).

Abundant precipitation can be beneficial by reducing the potential for sulphide mineral oxidation. The large excess of precipitation in the Elliot Lake region suggests that high moisture contents and shallow water table conditions will prevail in pyritic slimes. This condition also has a negative effect, however, if it is desirable to control the flux of water through the tailings surface. Attempts to divert precipitation from entering the tailings will likely require sophisticated cover designs. There is no cost-effective technology available that involves soil or earth covers, for example, that has been demonstrated to eliminate infiltration into tailings in similar humid environments.

In contrast, the small amount of net precipitation that occurs in non-pyritic Saskatchewan tailings will be beneficial by limiting the throughput of contaminated water. Desiccation of the tailings surface associated with the arid conditions will need to be addressed when choosing the surface treatment options for decommissioning.

# 4.0 APPRAISAL OF SLIMES MANAGEMENT OPTIONS

## 4.1 General

This section of the report presents an overview and appraisal of slimes management options.

It has been well-established by now that "management" of uranium tailings cannot be considered strictly in the context of planning and operation of a mine. When active discharge ceases, uranium tailings "management" must continue until such time as the deposited tailings and associated discharges are considered to be environmentally acceptable.

The planning, design, operation, close-out, site reclamation and monitoring of a uranium tailings management facility are dynamic components of an ongoing process. Constant modification may be required, and would depend upon the actual performance of the facility. Site reclamation for surface impoundments (the most common tailings management facility) is currently a process of trial and error, because there is very little experience by which to judge the likely long-term success of measures adopted (Vick, 1983).

Historically, uranium tailings management facilities in Canada have been planned and have evolved almost exclusively as surface impoundments. Other tailings management schemes exist, and the potential options can be classified in terms of storage location. These include:

- underground (mine backfill);
- offshore (marine disposal);
- lake basin;
- excavated pit;
- surface impoundment.

Quantitative methods of comparative evaluation of tailings disposal alternatives have been developed (Vick, 1983; Caldwell and Welsh, 1982), generally involving matrix evaluation procedure with weighting factors assigned to selected management objectives

(e.g, cost, long term stability). However, quantitative evaluation is not a generic process - site-specific factors and intangible items such as public perception and "political" climate have to be considered to effectively evaluate each case. Therefore, the discussions and evaluations which follow are necessarily qualitative, and focus primarily on the effectiveness of each method for providing long-term physical and chemical stability of uranium slimes masses in the environment.

## 4.2 Optional Storage Locations

### 4.2.1 Underground

Placement of tailings underground has long been practiced, not for the disposal of tailings, but to assist in mining operations (Vick, 1983). Underground mine backfilling with tailings has traditionally been practiced for ground support, to maximize ore recovery and/or to provide a working floor. Increasingly, however, underground tailings storage for itself is being viewed as a legitimate tailings management alternative, as the cost and regulatory pressures associated with surface disposal increase.

High permeability and low compressibility are necessary tailings properties for the traditional backfill applications. The tailings must dewater rapidly because there is insufficient area underground for a decant pond similar to that used for surface disposal. This normally restricts backfill tailings to the sand fraction only.

The use of slimes as underground backfill is therefore relatively uncommon and is not likely to increase unless finer grinding of tailings in the future reduces the amount of available sand. In addition, placement of greater volumes of tailings in the mine would restrict flexibility in planning and operating the mine. Even if the tailings are placed underground after mining operations cease, a future increase in ore value could make it desirable to re-open the underground workings to extract more ore. These limitations notwithstanding, underground storage of uranium slimes generally deserves more emphasis in overall tailings management planning. Particularly in the older mining districts, where significant unused space may be available.

Underground storage of slimes provides the following advantages:

- o the slimes would be placed in the original location of the ore;
- o no structures are required to ensure physical stability of the tailings;
- o there is the strong potential to minimize contaminant releases to the environment because of smaller water fluxes associated with deeper zones in the subsurface; and
- o pyritic slimes would not be subjected to significant oxidation below the watertable and, therefore, acid generation would not likely be a consideration in the long-term management requirements.

The disadvantages of underground storage of slimes include the following:

- o rapid placement of slimes in a slurry would be impractical because of space restrictions for decanting during settlement and consolidation;
- o significant clay contents in the slimes would aggrevate settlement and decant problems;
- o low densities of slime-enriched tailings result in volumes which may be larger than the volume of mined rock; and
- o fractured rock environments add significant complexity to the prediction of contaminant pathways and rates of movement.

Dewatering of slimes prior to placement underground can solve the problems of excess water and poor settling characteristics. Dewatering small volumes of slimes is practiced in Europe and South Africa (Vick, 1983). High clay contents may negate this option. Obviously, a proven economical method of underground slimes placement at rates compatible with normal Canadian production levels would be required. Alternatively, other techniques may be advantageous to enhance settling and rapid consolidation of slimes underground. The long-term environmental safety advantages of underground placement may justify such a development study in mining districts where unused underground storage space exists and all mining reserves are considered exhausted.

### 4.2.2 Marine Offshore

Offshore disposal of non-uraniferous tailings in the marine environment has been practiced at several mines in Canada, the Philippines, Chile and Central America (Vick,

1983). To date, the practice of offshore disposal of uranium tailings has not been documented. Offshore disposal of tailings has traditionally generated controversy, public concern and political attention. This controversy probably arises from a public perception that offshore disposal consists merely of dumping toxic waste in an unconfined space where it disperses in an uncontrolled fashion.

Studies of ongoing operations show that impacts on water quality and biota are low (Poling, 1979; Pelletier, 1982; Hay, 1982) for some disposal operations, and offshore disposal areas quickly become rehabilitated after discharge ceases. Excess turbidity and unexpectedly distant deposition of tailings have also been reported (Ripley et al., 1978), however, suggesting that further testing may be required to manage offshore disposal in an acceptable fashion.

An essential technical pre-requisite in planning an offshore disposal scheme for uranium slimes would obviously be, a very good characterization of the parameters which control the long term stability of that environment (e.g., seismicity, currents, temperature and density gradients, biota, etc.).

Offshore deposition of tailings provides the following advantages:

- o large dilution factors are generally associated with potential contaminant releases; and
- o little need for physical containment structures.

A number of uncertainties exist in offshore deposition, with the resulting disadvantages:

- o slimes would be particularly sensitive to changes in physical transport processes such as currents and temperature inversions;
- o contamination could spread over large areas with less potential for remedial action; and
- o dispersion of slime, in general, would be greater for slimes than for whole tailings.

There appears to be need for an in-depth evaluation of this method if it is to be applied to uranium mill tailings, particularly the slime-enriched fraction.

### 4.2.3 Lake Basin

Underwater placement of tailings, in lake basins, has been extensively practiced in Canada. The original lake basin is usually filled with tailings, and dams are required in topographic lows. In practical terms, this transforms the storage facility into a classical surface impoundment.

In this report, lake basin placement is defined as the engineered underwater management of tailings within an existing lake. Conceptual studies have been conducted for the underwater placement of uranium tailings in the deep Quirke Lake basin (Golder/MacLaren, 1980; BEAK, 1982) in Elliot Lake. One case history for shallow lake disposal is documented for Mandy Lake in Flin Flon where sulphidic tailings have existed for more than 30 years. This was not the intended management scheme at this site, but provides case-history evidence of controls on acid generation in these otherwise exposed tailings.

Underwater lake management would involve the placement of tailings into a permanent submerged state, in a natural lake setting. It therefore offers most or all of the advantages of offshore disposal, without the degree of uncertainty surrounding physical confinement and long-term physical stability of the tailings mass, that exists in the offshore case.

If properly planned and executed, this type of storage does not require destruction of the lake. A minimal depth of water, allowing post-operation reclamation of the lake, can be pre-determined and engineered solutions provided for this problem, including placement of an underwater cover on the tailings mass to improve its stability and reduce sediment scour and re-suspension problems. The minimum depth of standing water will depend on the thermal characteristics of the lake, in addition to flow hydraulics.

Underwater lake management of uranium mill slimes provides the following advantages:

- deposition in a natural sedimentation environment resulting in enhanced physical stability;
- ability to provide further isolation in the confined environment of the lake bottom through application of appropriate covers;

- o potential to choose a natural discharge lake that exhibits net groundwater flow into the lake, thereby reducing potential pathways for aqueous phase contaminant transport;
- o potential for geochemical barriers such as organic layers to induce reducing conditions that would control acid generation in pyritic slimes and reduce metal concentrations in water leaving the tailings;
- o technology for underwater tailings placement is currently available through active offshore management of other tailings (Ellis, 1982); and
- o monitoring of water quality is simplified in relation to other options.

The disadvantages of underwater lake management include the following:

- o the use of flocculents or other treatment would likely be required, especially for slimes with large clay contents;
- o a suitable lake may not be available within a practical distance; and
- o some uncertainty with respect to chemical stability and leaching behaviour.

The available degree of control on long term physical stability and the deposition in a permanent submerged state, make this option one of the more attractive ones from an environmental standpoint. Obviously, however, other site-specific factors, including cost, that relate to the proximity of a suitable lake or lakes, will also weigh heavily in the selection of the preferred option.

### 4.2.4 Excavated Pit

Disposal of tailings in abandoned open pit mines has been practiced extensively in the United States. Recently, the disposal of uranium tailings in specially excavated pits or in mined-out open pits, has virtually become a regulatory requirement in that country (Vick, 1983).

Uranium mining in the United States is located in an arid environment, where coastal or lake basin deposition options are virtually non-existent and where most mining is done by open-pit methods. Because of the arid climate, raised surface impoundments present problems of very low moisture conditions in the long-term, plus the attendant problems of erosion susceptibility, which has led to the preference of storage in excavated pits.

The Canadian "arid" environment differs significantly from that associated with the U.S. deposits. There is a net water surplus in Canada, and the watertable is usually close to ground surface. However, the American experience with pit discharge and filling procedures can be very relevant to similar storage concepts in northern Saskatchewan and in the Northwest Territories, where most mining operations to date have been conducted in open pits. A study at Rabbit Lake was recently conducted on the feasibility of transferring tailings from an abandoned surface impoundment to an open pit, as a close-out and site reclamation alternative to the surface impoundment. Experience from this operation will be valuable in evaluating options for future open-pit management schemes.

In open pit mining, because vast volumes of waste rock are removed and disposed of separately, the volume of unused space which may be available to receive tailings is generally much larger than the volume made available by underground mining. The backfilling of open pits is also less restrictive from a planning perspective, especially when further underground mining is expected for the ore body. In some cases, it may be desirable to excavate special pits for the disposal of tailings from high grade ores.

The surface area of most mine pits is relatively small, in comparison to an equal storage capacity surface impoundment facility. Hence, the area available for a decant pond is restricted and excess water often must be pumped to separate polishing and settling ponds for treatment and/or release to the environment. In an arid environment, such ponds can be designed as "evaporation ponds", eliminating effluent discharge to the environment. This option may not be feasible even in northern Saskatchewan where excess precipitation is expected with insignificant evaporation.

Use of flocculants to improve settling characteristics may be required, in particular where the clay mineral content is significant. Relevant experience with backfilling of open pits with clay wastes is available from the Georgia Kaolin mining industry in the United States.

The advantages of slimes management in worked-out open pits include the following:

- the need for slimes management will likely correspond to the period when underground mining is conducted and open pit operations have ceased;

- o the slimes will be well-contained and physically stable;
- o the advantages of underwater management may apply if the natural watertable level remains above the final surface of the tailings;
- o slimes management could be coupled to open pit reclamation;
- o backfilling of open pits and subsequent loss of access to mining is not restrictive when underground mining is planned for the ore deposit; and
- o open pits generally occupy relatively small areas that would be amenable to surface reclamation.

The disadvantages of slimes management in open pits can be summarized as:

- o excess water and slow particle settling will require special attention in the open pit;
- o uncertain rock permeability due to fracture networks may cause water control problems in the associated underground workings if slimes are being deposited contemporaneously; and
- o monitoring would be complicated by fracture-flow conditions in the subsurface.

### 4.2.5 Surface Impoundment

A surface impoundment is defined here as a facility where the tailings mass is contained on the ground surface by one or more embankment structures. Surface impoundments are the most widely used types of tailings management facilities (Vick, 1983).

Containment structures for tailings impoundments typically vary from conventional water-retaining embankments, built from borrow materials, to embankments raised by hydraulic filling techniques, using discharged tailings. These tailings embankments can be raised by upstream, downstream and centreline methods (Vick, 1983).

Depending on the local water balance, tailings discharge methods and other factors, the impounded tailings can be maintained either completely submerged during deposition or in a relatively unsaturated condition on temporary "beaches" formed by the peripheral discharge method and the slope that the settled solids assumes. A decant pond is normally maintained at a remote location from the point(s) of discharge. Further details

of the various options for development of a surface impoundment are given in Section 5.0 of this report.

A surface impoundment for uranium slimes is the option which probably requires the most "active" management of all those considered here. Constant control must be maintained on contaminant releases to air, surface water and groundwater environments during the operation. During decommissioning and site reclamation, measures should address alternatives for long-term physical and geochemical stability, which may involve "passive" or "active" solutions, and possibly involve "perpetual" monitoring. Because it is the most widely used option for uranium tailings management, surface impoundments are also the facilities for which there are better defined regulatory requirements and a greater body of performance information.

In relation to other management options, a surface impoundment clearly involves greater uncertainty about long-term physical stability than either underground or excavated pit storage options. This is particularly applicable to the long-term erosional stability of the impoundment surface, the long-term structural stability of containment structures (embankments) and long-term integrity of engineered seepage barriers (e.g., grout curtains, "impervious" cores).

Surface impoundment of slimes presents the following advantages:

- o the lower hydraulic conductivity of the consolidated slimes will help to reduce the flux of water-borne contaminants; and
- o larger areas are available for decanting and settling of the fine-grained tailings.

The disadvantages of surface impoundment of slimes include the following:

- o the lower strength of the slimes will decrease their acceptability for use in the construction of embankments and therefore increase the need for borrow materials to build retaining structures;
- o the degree of difficulty in site reclamation (placement of soil covers, vegetation) will also increase due to the lower strength, particularly when the clay mineral content is significant;

- o finer grained tailings, particularly with significant clay mineral content, will occupy more volume per unit weight than the whole or unsegregated tailings so that volume reduction, resulting from sand removal, may not be realized; and
- o increased fines content may lead to higher costs for effluent treatment than before, in terms of settling suspended solids during the operation.

In summary, capital and operating costs may rise slightly due to greater solid and liquid phase storage volume and effluent treatment required per ton of tailings than for unsegregated tailings; however, long-term management costs, in terms of close-out/site reclamation and post-operation effluent treatment, may be reduced.

## 4.3 Selection of Preferred Storage Option

There are methods for quantitative evaluation of alternative tailings management options or storage locations. However, a valid quantitative evaluation can be made only on a case-specific basis.

Some of the factors which will influence the selection of a preferred storage option are:

- o capital, operating costs which may include costs of site reclamation, close-out and long-term maintenance costs;
- o environmental, legal and regulatory requirements;
- o long-term post-closure physical and geochemical stability and associated degree of control required and available; and
- o compatibility of the tailings management scheme with the other aspects of mining and milling.

There are some basic inherent differences among the five major alternative management and storage options which can be summarized by the following:

- o marine offshore and lake basin storage are "passive" management options, which are designed to prevent effluent treatment; however, initial engineering and development costs may be high;

- o underground, excavated pit and surface impoundment options all require effluent management which may include recycle, evaporation or treatment during the operating, and possibly during the post-operational, period; and
- o groundwater impacts, through seepage, are more likely to be of concern for surface impoundments, as a result of the higher seepage gradients associated with that type of facility. Groundwater seepage impacts are unlikely to be of concern in marine offshore and lake basin areas, which generally represent areas of net groundwater discharge.

The question of proximity to suitable disposal locations can quickly eliminate some of the options, such as "worked out" underground or open pit mines and coastal areas, on the basis of cost alone. The geographic location of present uranium mining districts in Canada and their respective state of development would indicate that use of either surface impoundments, lake basins or open pits are the most preferred options for uranium slimes management in the foreseeable future. Of these, surface impoundments are likely to be the option which will continue to dominate disposal practices. Open pit filling should not be excluded from consideration, but more performance data from new sites, such as the Rabbit Lake facility, will be required before detailed evaluations can be conducted. The remaining sections of this report, therefore, focus on the positive and negative aspects of slimes management practices related to surface impoundments.

# 5.0 MANAGEMENT OPTIONS FOR SURFACE IMPOUNDMENTS

## 5.1 Site Selection

### 5.1.1 Valley

Valleys are generally the preferred sites for tailings impoundments. In some circumstances, small lake basins may be used, but this entails the sacrifice of natural resources and, therefore, require special considerations and justification. In still other cases, where flatland topography dominates, a raised impoundment or stack may be the only available site option.

Because uranium tailings impoundments generally require extensive containment structures, selection of a surface impoundment site will generally be governed by maximizing the ratio of tailings mass stored to containment construction costs. Other considerations, such as decommissioning requirements and their associated costs, will also play a role in deciding where to locate the disposal facility. The selected option may not be the best site in terms of current capital and operating costs. For example, a deep valley site with only one large high dam may have attractive capital and operating costs, but may be more costly to decommission than a shallow valley with a number of low dams.

Disposal of slimes, as opposed to "whole" tailings, increases the demand for borrow materials to construct containment structures (dams and covers) because the slimes tailings will generally not constitute acceptable construction materials. All other factors being equal, this may be the only undesirable effect of managing slimes, as opposed to whole tailings, in a valley site.

### 5.1.2 Lake Basin

Deposition of tailings in lake basins has been practiced extensively in Canada. Deposition is generally carried out until the waterbody is completely infilled with tailings and containment structures (dams) are built at one or more of the basin outlets.

Deposition of uranium slimes into a lake presents some disadvantages in relation to use of a valley site. Firstly, the tailings discharged into the waterbody will assume a lower density than those discharged onto "beaches" in valley sites. The lower density implies a weaker and more pervious tailings mass. Secondly, effluent management problems related to suspended solids will probably be aggravated in a lake basin setting, particularly if the slimes contain a significant clay fraction.

On the other hand, deposition into a lake probably ensures saturation of tailings mass over a significant part of the operating life of the facility. This may be advantageous from an effluent treatment standpoint for acid generating tailings in a semi-arid setting. If properly engineered, such a facility may be maintained in surface-saturated condition for the long-term management of the facility after close-out.

### 5.1.3 Stack or Raised Impoundment

A stack or raised impoundment may be the only available option for a flatland setting. Due to the low ratio of stored mass to containment construction costs in these cases, the containment structures are generally built hydraulically from tailings.

Because of concern with potential radionuclide releases via seepage through perimeter containment structures, uranium tailings impoundment structures are generally designed to be "impervious", and are constructed with compacted borrow materials. Constructing such an impoundment with "impervious" dams for uranium slimes would not be econmically practicable.

Experience with construction of perimeter containment with slimes is virtually non-existent. All hydraulic methods of construction (perimeter spigotting and cycloning) pre-suppose the existence of a "sand" fraction for the outer-wall construction. However, depending on the actual grain size, it may be possible, with multi-stage cycloning and polymer addition, to obtain from certain slimes an underflow material which will settle quickly and provide adequate containment. In any event, perimeter slopes would have to be quite flat to ensure stability, and erosion protection would be required.

In summary, raised impoundments will have very restricted, if any, applicability for uranium slimes. A remote possibility exists for the case of non-acid producing slimes in

a semi-arid environment, where seepage releases will be low. Abundant historical information for this type of management scheme is available from the South African gold mines. However, with the net precipitation and relatively high water table conditions, even in Saskatchewan, the long-term behaviour of raised impoundments is highly uncertain.

## 5.2 Basin Filling Scheme

An essential step in developing a tailings management scheme is to plan the sequential filling of the basin. This allows development of construction stages for the containment dams, in order to reduce capital or start-up costs; it also allows planning of discharge points, sedimentation pond location and associated decant facilities.

### 5.2.1 Central Pond Schemes

Because of the special long-term stability requirements of uranium storage facilities, it is important that the basin filling scheme, for whatever type of site, also be selected so as to reduce the cost of site reclamation. This includes consideration of final position of the low point (usually the sedimentation pond) in the tailings impoundment for the construction of a secure long-term spillway.

The basin filling option, traditionally associated with a stack or raised impoundment, involves a centrally located sedimentation pond. Problems with close-out, particularly provision of a safe-permanent spillway through tailings, have, in recent years, moved planners to avoid this option.

### 5.2.2 Perimeter Pond Schemes

There is a recent trend to develop tailings deposits with a gradient towards one side, where the sedimentation pond is located. Generally, this pond is retained by either a natural height of land or by a low water-retaining dam.

All other factors being equal, a larger and shallower sedimentation pond will be required to control suspended solids in the slimes case than in the "whole" tailings case. This need for a large shallow pond should also be adequately recognized in the initial planning of

the site development and filling, including an allowance for provision of secondary settling ("polishing") ponds.

In order that a secure long-term spillway can be easily established for the impoundment, it is best to develop the filling scheme to ensure the primary sedimentation pond is retained by natural ground or a very low structure. This requirement may not be easily met, and some compromise will be necessary in certain circumstances, such as in a steep narrow valley site. Meeting the low-perimeter-pond-dam objective will be more difficult in the case of slimes as opposed to whole tailings, because flatter overall beach slopes will result in a required increase in containment height relative to a fixed discharge point.

## 5.3 Containment Structures

### 5.3.1 Compacted Borrow Dams

Concern for radionuclide releases via seepage through dams generally leads to the use of "impervious" dams for uranium tailings impoundments. These dams are designed and constructed as conventional water-retaining structures from compacted borrow materials.

The dams can be homogeneous or zoned, depending on availability of materials and other criteria. Some existing dams with centrally located cores actually incorporate an upstream shell of compacted tailings sands. This type of feature will not be possible with slimes impoundments, as mechanical handling and compaction of slimes will be impractical. Hence, there will likely be a total dependence on borrow material sources for the containment structures for slimes impoundment.

The long-term stability of containment structures for uranium tailings impoundment has been reviewed by Steffen et al. (1986). The trend towards impoundment of finer-grained tailings (slimes) is not likely to influence the design of compacted borrow dams. Long-term erosional and seismic stability will likely remain the most stringent requirements.

### 5.3.2 Hydraulic Fill Dams

Raised tailings impoundments or stacks are generally contained by perimeter dams built by hydraulic fill methods from tailings. A reduction and eventual elimination of the sand fraction of tailings, prior to discharge into the impoundment, will severely restrict the applicability of this type of containment structure for uranium tailings. The application of this type of containment structure would be restricted to a semi-arid environment with non-acid generating uranium tailings. Multi-stage cycloning would be required to produce a high percent solids underflow of sufficient quantity to create the perimeter structure. The environmental acceptability of this solution would depend on the release of radionuclides via seepage through the perimeter.

The low permeability of slimes is a positive environmental attribute of hydraulic fill (tailings) dams for perimeter containment. However, practical aspects of wall construction and concern about long-term stability of slimes embankments will probably limit the applicability of this technique to special cases, such as semi-arid zones, flatland topography and non-acid generating tailings.

### 5.3.3 Grout Curtains

Grout curtains have been installed below "impervious" compacted borrow dams for the control of seepage from uranium tailings impoundments. Grout curtains are used to reduce the seepage flux below dams. The need for grout curtains in the case of slimes impoundments is likely to decrease. This will occur because the seepage rate and release of contaminants from slimes impoundments is likely to be lower than from "whole" tailings impoundments.

The long-term performance of grout curtains has been questioned (Steffan et al., 1986), particularly in the context of acidic seepage releases from uranium tailings impoundments. This may not be problematic for slimes, especially with significant clay contents. In addition, long-term monitoring, maintenance and possibly replacement of these barriers is feasible and, therefore, their use is likely to continue where necessary.

## 5.4 Treatment in the Mill

### 5.4.1 Additives

Certain measures are often required to treat the tailings prior to transport and discharge to the impoundment. Additives to control pH of the slurry, to reduce toxic unspent reagents or to improve settling characteristics of the solid phase are examples of treatment possibilities.

After an acid leach extraction process, lime is added to raise slurry pH to neutral conditions, prior to discharge. In pyritic tailings, sufficient lime is added to raise the pH to the range of 10-11, prior to discharge. The higher pH is imposed to provide a greater buffering capacity to attenuate acid generation, particularly in surface impoundment facilities, where the tailings are exposed to the atmosphere during the operating phase.

Polymers are another type of additive that can be used in treatment of the tailings slurry at the mill. When tailings contain a significant clay mineral fraction, suspended solids represent an effluent quality problem in the surface discharge from the impoundment. Polymers can be added at the mill to promote flocculation and improve settling characteristics of the tailings. Lower densities in slimes due to the flocculation phenomenon and associated increase in volume required for the impoundment represent a negative aspect of polymer treatment. As an alternative, polymers may be added prior to the polishing pond. In either case, this type of treatment will likely play an important role in clay-rich slimes.

### 5.4.2 Thickening

Thickening is a method to reduce the amount of process water discharged with the solid fraction of the tailings. This can be done either through use of hydrocyclones or thickeners; the latter are more common.

Thickening has the benefits of:

- maximizing process water recycle in an arid environment situation, where water resources are limited and process water reclamation from the tailings pond is less cost effective due to distance, topography, etc. and

- reducing segregation of tailings upon deposition and reducing height of containment structures, in surface impoundments (Robinsky, 1979).

### 5.4.3 Dewatering

Dewatering of tailings through use of presses and filters is practiced in Europe and South Africa, for relatively small scale uranium mining operations. It is considered that this technique may have limited use for larger scale operations such as those in Canada, particularly for slimes, which are especially difficult to dewater in this way. The dewatering operation at Collins Bay in Saskatchewan is an example of this practice. The use of these dewatering techniques for the smaller volumes of sludge from tailings effluent treatment might be practical, particularly for acid generating tailings, which produce significant volumes of sludge.

## 5.5 Discharge Methods

### 5.5.1 Subaqueous Discharge

Sub-aqueous discharge involves placement of the tailings under continuous fully, submerged conditions. This practice is seldom used in a "dry" land impoundment situation, unless it is required to control acid generation in tailings from massive sulphide ores and/or for suppression of radon gas emanation in storage of uranium tailings in arid environments. Subaqueous discharge in a surface impoundment may require the use of a floating discharge method of distributing the tailings throughout the impoundment, while controlling the decant of effluent. This method has been in operation at Ranger Uranium, in Australia and is planned for the massive sulphide tailings, at the Neves-Corvo high grade copper mine in Portugal. Both sites are located in arid environments.

One of the problems associated with this method of discharge is the resulting, relatively low density of the deposited tailings, which increases storage costs per unit weight of tailings produced. The problem increases as tailings become finer.

Full submersion of a surface impoundment in a severe arid environment, after close-out of the facility may not be practical. However, full submergence, via subaqueous disposal, can greatly reduce effluent treatment requirements. Ideally, zero discharge

may even be achieved during the operating period, through process water recycle in an arid environment.

### 5.5.2 Subaerial Discharge

Subaerial tailings discharge is a technique involving deposition of tailings in thin layers, allowing each layer to "dry" prior to further accumulation in a given area. This method requires that tailings be discharged with spigots from a main pipeline in "sheet" fashion, rather than as a single "cone" from "end dumping" from the main line. Frequent rotation of the discharge areas is required to limit the lift thickness and allow the intended drying effect. This requires an extensive pipeline system to allow such rotation. Underdrains are also beneficial to dewatering and settlement of the tailings.

It should be noted that "subaerial" deposition, in practical terms, does not differ significantly from the long established practice of constructing perimeter containment by the "upstream" method, with spigotted tailings. The added feature of "subaerial" deposition, is the systematic rotation of discharge areas to achieve drying of thin lifts before further deposition.

The conventional objective of the subaerial discharge method is therefore to achieve a denser deposit, with associated benefits that include:

- lower storage costs per unit weight of tailings;
- lower hydraulic conductivity of tailings mass;
- good lateral drainage to promote consolidation; and
- higher strength of tailings mass (better stability and trafficability).

The method works best for fine-grained tailings in arid environments. Significant consolidation of the thin lifts can be achieved when drying is almost complete. This method is not advisable for acid-generating tailings for which exposure to wetting and drying cycles exacerbates the oxidation of sulphide minerals.

This deposition method could be used to meet two objectives in the Canadian environment. Pyritic slimes could be deposited in small impoundments to maintain water saturated conditions. The tailings would not be submerged, but would retain a high

degree of moisture even after consolidation. Non-pyritic slimes with a significant clay content could be deposited subaerially in larger basins for conventional purposes. The large surface area in combination with an arid environment, would allow the necessary drying. Dust and radon emanation would be dampened by the presence of clay minerals.

Subareal deposition represents a solution to the problem of tailings settlement and consolidation that requires special treatment for many of the other methods. It is a flexible process that can be applied advantageously to acid-generating slimes and those with significant clay mineral contents. The performance of the Key Lake facility will provide useful data on which to base modifications for future facilities.

### 5.5.3 Thickened Discharge

Thickened discharge results in unsorted deposition of the solid phase when the solids content of the slurry is increased to 50 to 70 percent solids by weight, through the use of a tailings thickener at the mill (Robinsky, 1979). Viscous behaviour for the finer fraction of tailings starts at relatively lower solids content (higher dilution) than for coarser grained or whole tailings. Thickened deposition results in steeper beach gradients and less or insignificant segregation of the tailings solids, by size. The lower degree of segregation resulting from this process may or may not have an advantage in the deposition of slimes. Thickened discharge would certainly result in less water discharge, and would reduce the need for containment structures designed for water retention.

Surface erosion of the steep slopes would probably limit the applicability of this method to areas of low seismicity and areas where erosional cover can be applied. The steeper slopes, in an arid environment could also result in faster drying of the deposit surface which would exacerbate acid generation in pyritic tailings.

Thickened tailings facilities in Canada include Kidd Creek and Selbaie Mines in relatively humid, low seismicity areas and Collins Bay and Amok in semi-arid areas. Very limited information is currently available on the behaviour of thickened tailings in arid or semi-arid environments.

### 5.5.4 Conventional Discharge

Conventional practice in discharge of tailings is governed simply by available storage space and the need to minimize overall pipeline length and pipeline relocations. This tends to result generally in open-end discharge (i.e., "end dumping") from a few selected strategic locations, with infrequent changes of the discharge location.

This practice with unsegregated tailings has led to the development and subsequent drying of inactive sandy beaches. In some pyritic tailings impoundments, this has resulted in cases of acid generation with the attendant problems of effluent treatment and potential groundwater contamination.

The deposition of slimes by this method is less problematic, particularly in humid environments. Capillary action in the fine-grained tailings should maintain high moisture levels even in beach areas so that pyritic tailings will be less affected.

The major problem with tailings deposition with long beach areas relates to the accumulation of the finest grain-size fractions in the vicinity of the down-stream pond. This area of "slimes" accumulation is generally untrafficable during operation, and would require dewatering to induce consolidation. Experience in gold milling operations in Ontario, however, has shown that the beach areas drain rapidly even for very fine tailings (50% minus 400 mesh) and can be reworked with heavy machinery (F. Firlotte, 1987, pers. comm.).

Gold mining experience has shown that the distance to the tailings pond is critical in maintaining well-drained and trafficable beach areas. When the topography is utilized to provide reasonable gradients between the discharge area and the pond, the slimes can drain rapidly to an extent where trafficability is not a problem.

It should be remembered that the current gold tailings do not contain significant quantities of clay minerals and, therefore, would be more representative of Elliot Lake tailings with respect to the granular structure and physical stability. The effect of high clay contents on drainage and trafficability using long beach areas is not known.

## 5.6 Effluent Management

### 5.6.1 Zero Discharge Schemes

Effluent management includes some or all of the following practices:

- o solid/liquid phase separation in primary settling and secondary "polishing" ponds,
- o recycle of clear effluent to the mill process,
- o treatment of the effluent for mill recycle and/or discharge to the environment.

In a "zero-discharge' scheme there is no effluent discharge to the surface water environment, during the operation of the facility, but there may be inadvertent discharge to groundwater. Generally, this is only possible at locations where there is no net precipitation (arid environment) and when the metallurgical extraction process in the mill can tolerate a high degree of recycle of process waters from the tailings slurry. This type of effluent management is commonly practiced at uranium mine facilities in the arid environment of the Southwestern United States. Evaporation ponds are often provided separately from the main tailings storage facility, for that specific purpose.

The tolerance of the metallurgical extraction process to effluent recycle is very difficult to predict, since it is dependent on a complex combination of factors, including ore mineralogy and the reagents utilized. This tolerance can only be established in actual practice, after the facility is in operation. It is very difficult to achieve zero-effluent discharge when this scheme is heavily dependent on the mill recycle. In areas of very high net evaporation (e.g., southwestern United States), there is less dependence on mill recycle because of the efficiency of evaporation ponds. But, in Canada, evaporation ponds will not likely be efficient and zero discharge would be heavily dependent on the metallurgical practicability of effluent recycle.

Zero-discharge schemes reduce or eliminate effluent treatment requirements, which is an advantage, particularly with acid generating tailings. A combination of subaqueous deposition and zero-effluent discharge would be the ideal combination for sulphide tailings, in an arid environment.

Finally, reduction or elimination of the contribution from external watersheds would also be a key to achieving the required tailings basin water-balance, for a zero discharge scheme. This normally requires the construction of diversion works. Such diversion works would likely be an essential part of a close-out and site reclamation scheme in any case.

### 5.6.2 Treatment and Discharge Schemes

The most commonly practiced form of effluent management involves the treatment and discharge of excess water from the tailings basin to the environment. Treatment commonly involves the use of barium chloride for precipitation of dissolved radionuclides and lime addition for neutralization and co-precipitation of dissolved metals. This treatment can either be carried out in a mechanical plant facility (e.g., Rio Algom's Stanleigh property, Key Lake) or in ponds.

Relatively large volumes of precipitates (sludges) are produced by effluent treatment at facilities where acid generation occurs. The sludges will contain higher concentrations of many chemical constituents of concern than those found in the tailings solids. To date, there is no experience with the long-term or permanent storage of these sludges.

Properly instituted management of pyritic slimes should reduce the quantities of sludge produced because less oxidation will occur. The management scheme should address the need to retain moisture in the tailings during the operation of the impoundment. Sludge management for slimes, however, should not be significantly different than that for unsegregated tailings.

## 5.7 Seepage Management

The control of seepage from tailings embankments has been the focus of much effort in tailings disposal. Infiltration that enters the surface of the tailings must exit either through the embankment when it is permeable and hence discharge to nearby surface waters, or through the underlying geologic materials to become part of the groundwater flow system when the dam is impermeable.

The tailings porewater that appears as seepage will contain concentrations of a number of radionuclides and, in some cases where sulphides are present, may be acidic and contain elevated concentrations of some metals. It will, therefore, be necessary to decide on the most desirable pathways for the tailings seepage to follow, in order that the impact to the environment is minimal. The management of seepage must also address related issues such as consolidation of the tailings and possibly active dewatering schemes to promote stabilization of the tailings mass.

Active drainage of the slimes impoundment would actually be desirable for water level control to enhance stability. Drainage options are discussed by Caldwell and Welsh (1982) and Charlie et al. (1983). In fact, without drainage, the slimes could remain untrafficable for long periods of time (Hanney et al., 1980).

Currently, seepage of tailings porewater adjacent to the embankment or retaining dams is observed at virtually all operating impoundments. This condition results from the input of tailings process water that causes ponding behind the embankment. The long-term behaviour of the tailings after decommissioning is expected to differ significantly from those during operation. Therefore, the long-term aspects of tailings seepage must be addressed.

Kealy and Busch (1979) discussed the importance of groundwater flow modelling to predict seepage rates and the location of the watertable within the tailings in the embankment. These are key considerations for planning and implementing the disposal design. The shallow groundwater flow systems that commonly develop below active tailings impoundments usually result in discharge some distance downgradient (i.e., seepage) at surface water locations. The length of groundwater flow pathways for the tailings porewater and the geologic materials encountered will influence the final concentrations of radionuclides that arrive in the surface water in the region of, or down-gradient from, the tailings impoundment.

The results of contaminant transport modelling (Barbour and Krahn, 1983) suggest that seepage into the groundwater system would be advantageous to the reduction of radionuclide concentrations that eventually arrive in the surface water environment. The advantage occurs during the slow movement of this tailings porewater in the groundwater domain where time is available for radioactive decay. Furthermore,

geochemical reactions may occur between the porewater and the solids so that attentuation of the radionuclides and other chemical constituents is possible.

This condition is evident at the Nordic mine tailings site, for instance (Dubrovsky et al., 1985), where acidic tailings porewater is migrating through the underlying sands and gravels. The rate of water movement in these sands and gravels is fairly rapid, but the goechemical reactions occurring between the acidic porewater and the carbonate geologic materials attenuates the movement of most chemical constituents of concern in the affected water. The movement of many chemical constituents is estimated to be about 300 times slower than the movement of natural groundwater in the area. This is somewhat of a special case related to the acidic porewater from the Nordic tailings migrating through a carbonate till, but similar attenuating effects are possible in other systems during groundwater flow.

In the humid to sub-humid Canadian environment, it is virtually impossible to alleviate all seepage through a tailings deposit. Engineered covers may be used to reduce infiltration. Some water will continue over the long-term to pass through the tailings, however, and discharge as seepage at the downslope region of the embankment, or to the underlying geologic materials to follow longer groundwater flow paths. It will be necessary to decide, during the development stage of the facility, what option is more acceptable, and whether pre-development engineering is required to attain this.

Seepage from the toe of a perimeter embankment implies immediate contact with surface water, and will likely involve treatment requirements before discharge off-site. This is undesirable for long-term management. The intentional routing of tailings seepage through the shallow groundwater flow system has the advantage of passive treatment and a buffer zone which can be monitored to evaluate its performance. This option would not be feasible or effective in all locations, but optimal site conditions could be located prior to facility development. Alternatively, subsurface barriers and/or covers may be required to obtain acceptable rates of contaminant releases.

## 5.8 Final Cover and Site Reclamation

### 5.8.1 Objectives

The purpose of site reclamation is to return the disturbed mine site to environmental and land use conditions similar to those prior to disturbance by mining. This may not always be possible, but at least certain issues should be addressed during reclamation. These include reduction of dust emissions, erosion and undesirable chemical releases either in the air or the water, control of seepage from the tailings, and general environmental aesthetics. There are a number of tailings sites in the Canadian environment where natural revegetation has occurred and where environmental impacts would appear to be minimal (reference needed). In other cases, however, especially where sulphide tailings are involved, revegetation is not likely to occur naturally. Although vegetation is not the primary focus of site reclamation, lack of it is generally indicative of other environmental problems. It may be necessary to develop other site treatment options to deal with these problems.

Tailings covers have been studied as one such option for site reclamation. There has been a great deal of effort involved in the study of covers for uranium mill tailings in the United States for the UMTRAP program (D'Antonio et al., 1987) generally with a focus to reducing radon emanation from these materials. A major review of cover technology has been conducted in Canada by Steffen, Robertson, Kirsten (1986). This review was conducted for the NUTP and included information on covers and control structures for Canadian uranium mill tailings.

Basically, covers can be divided into four categories. These include soil covers (or natural sediments), water cover, vegetation cover and waste-rock cover. These covers have different objectives, and provide different types of control on the tailings surface. The overall objective of cover placement, however, is to reduce undesirable emissions and to provide some form of reclamation.

It was shown in Part 1 of this report that the two major deterrents to the surface remediation of slimes tailings include acid generation and poor consolidation. These issues must, therefore, be the focus of attention for the application of covers or other remedial activity. Other characteristics that should be addressed for reclamation of

slimes include the potential for significant consolidation, differential settlement and high relative proportion of chemical precipitates, especially gypsum.

### 5.8.2 Soil Cover

A soil cover on the tailings can be applied to reduce infiltration to provide a growth medium for vegetation, and to isolate the tailings from activity on the land surface. These covers may consist of a single layer of available soil material or may be engineered into a multi-layer complex cover system which would reduce infiltration of water and oxygen if necessary. The choice of soil covers would depend on the site-specific conditions, costs and actual requirements at a particular tailings impoundment.

Soil cover designs will not be dealt with here. However, the application of these covers to slimes will require that certain characteristics of the tailings be considered. Specifically, high watertable conditions and potentially significant consolidation in slimes should be expected. These characteristics will affect trafficability and cover stability.

Special techniques were used to construct covers on slime regions of a uranium tailings deposit in New Mexico (D'Antonio et al., 1987). These measures included the provision of extra time to construct the cover after relocation of existing tailings in order to avoid major displacement during consolidation. These concerns could be reduced if the facility were designed to enhance consolidation (increase tailings density) during the operating life of the tailings.

Hydraulically placed soil covers are an obvious alternative in large basins with poor trafficability. Coarse materials such as sand could be applied in a manner similar to tailings discharge. Sandy covers will provide loading to enhance consolidation, as well as drainage pathways, and will likely increase potential trafficability.

### 5.8.3 Water Cover

A water cover may be provided either by disposing of tailings into a natural surface waterbody, such as a deep or shallow lake, or by flooding of the tailings to maintain ponded conditions behind the tailings dam. Flooding of existing tailings is not usually feasible, however, because of potential stability problems and the difficulties inherent in maintaining artificially high water levels.

The more reasonable option for water cover exists in areas of natural sedimentation, such as is provided by natural lakes. Underwater disposal can be advantageous in at least one way. The case of the Mandy mine site in Flin Flon, Manitoba, is an example of the positive attributes of underwater tailings disposal (Monenco, 1985). This high sulphide tailings was deposited in a shallow lake and has remained there for more than 32 years. Very little oxidation of the abundant sulphides has occurred, except along the shoreline where some tailings are located above the water line. Vegetation has been established on the submerged tailings and organic decaying material is accumulating on the lake bottom. A number of animal species occur throughout the lake.

Water as a cover is suggested by Garga et al. (1983) and Smith and Zyl (1983) for the reduction of acid generation in sulphidic tailings. The chemical and physical processes that act to reduce the rate of acid generation in such an environment have been discussed and modelled by Halbert et al. (1983) and Nicholson et al. (1987). There is no doubt that acid generation will be reduced or effectively halted under such a cover. There are other considerations, however, that need to be addressed and are noted above.

Evaluation of the concept of underwater disposal of uranium mill tailings has led to some controversy and uncertainty about the radiochemical stability of the tailings (BEAK, 1982; Golder-McLaren, 1982). Further evaluation would be needed before such a design is initiated.

### 5.8.4 Vegetation Cover

If other environmental effects, such as contamination of groundwater and uptake of radium, are not considered to be problematic at a particular site, it may be desirable to simply rely on the invasion of indigenous vegetation across the surface of the tailings to provide a suitable means of disposal. As was discussed in Part 1 of this report, it is often difficult to develop vegetation on slimes because of the high moisture conditions that usually prevail in addition to the lack of nutrients within the fresh tailings. The degree of difficulty for revegetation increases significantly when sulphide tailings are encountered. If neither sulphides nor acid conditions are present, then revegetation by selected high-tolerance species may be possible.

There are numerous cases of tailings revegetation at non-uranium mines throughout Canada. One group that has been particularly successful is Inco, with over 1,500 acres of successfully revegetated abandoned tailings dams and dump sites (Van Cruyningen and Puro, 1987). Not all Inco tailings are composed of slimes, but large proportions contain high sulphide concentrations. It will be advantageous, and perhaps necessary, to plan for revegetation by assuring appropriate watertable levels in the slimes at uranium tailings facilities.

### 5.8.5 Perpetual Management

The ideal case for tailings site reclamation would be one where maintenance is not required and the system is self-sustaining and problem-free. Depending on site conditions, however, it may be necessary to provide some degree of control during the decommissioned phase. An example of this may be the requirement to treat seepage effluent that exceeds concentrations for specified radionuclides and/or metals. Perpetual management is rather undesirable, and should likely be avoided if other options exist.

Management decisions should be based on monitoring results and the observed performance compared to predicted behaviour. Corrective actions should logically be related to trigger levels for various measurements. For slimes, these would include the list of measurements for all tailings deposits, including radionuclide concentrations in effluent and in air. Additional characteristics that could require modelling include settlement resulting from near-term consolidation and long-term dissolution of chemical precipitates.

## 6.0 CONCLUSIONS

There are no unique methods or practices which are applicable and preferred for management of uranium slimes, under all combinations of climate, and site and tailings characteristics.

The three preferred first-order options of slimes management include:

1. excavated open-pit where available,
2. shallow surface impoundments, and
3. underwater disposal, where an appropriate lake is available.

The "preferred" designation refers to long-term reliability aspects, in terms of safe environmental containment of the waste - it does not include economic considerations. A relative rating of the options is given in Table 6.1 for the major climatic and tailings characteristics.

The use of a surface impoundment will be the only practical management option at most sites. In this context, a number of issues should be addressed to assure proper long-term management of slimes. These include:

1. enhanced consolidation for geotechnical stability and trafficability of the tailings;
2. seepage control; and
3. restriction of oxygen entry to the tailings if sulphides are present.

Second-order options were reviewed only for the case of surface impoundments. There is a large degree of inter-dependence between the various methods and practices in management of a particular surface impoundment facility. Table 6.2 provides a relative rating of the most effective methods for long-term management of slimes in tailings impoundments. It is noted that this general appraisal does not identify "preferred" methods under certain categories (e.g., site reclamation for acid generating tailings); only "adequate" and "inadequate" assessments have been made. In these cases, only a detailed assessment can determine a "preferred" method.

TABLE: 6.1 SUMMARY APPRAISAL OF STORAGE FACILITY OPTIONS FOR URANIUM SLIMES MANAGEMENT

CANADIAN CONDITIONS

| HYDROLOGY | SEMI-ARID ENVIRONMENT | | | | SUB HID ENVIRONMENT | | | |
|---|---|---|---|---|---|---|---|---|
| TAILINGS CHARACTER | Acid Generating Tailings | | Non-Acid Generating Tailings | | Acid Generating Tailings | | Non-Acid Generating Tailings | |
| DISPOSAL OPTIONS | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals |
| Underground | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| Offshore | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Lake Basin | 2 | 2 (1)? | 2 | 2 | 2 | 2 (1)? | 2 | 2 |
| Excavated Pit | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Surface Impoundment | 3 | 3 | 2 | 2 | 3 (2)? | 3 (2)? | 2 | 2 |

NOTES:
1. Slimes Disposal Options are ranked qualitatively in accordance with the system indicated in the Legend. If an option is not available or economically viable, the next option in rank shoud be considered.
2. Long term reliability is a dominant factor in the ranking of the options shown. For further details refer to discussion in report text.

LEGEND

1. - Preferred
2. - Adequate
3. - Doubtful (detailed appraisal required)

TABLE: 6.2 SUMMARY APPRAISAL OF OPTIONAL MANAGEMENT METHODS FOR URANIUM SLIMES IMPOUNDMENTS

CANADIAN CONDITIONS

| HYDROLOGY | | SEMI-ARID ENVIRONMENT | | | | SUB-HUMID ENVIRONMENT | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Acid Generating Tailings | | Non-Acid Generating Tailings | | Acid Generating Tailings | | Non-Acid Generating Tailings | |
| TAILINGS CHARACTER | | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals | With Significant Clay Minerals | Without Significant Clay Minerals |
| OPTIONAL MANAGEMENT METHODS | | | | | | | | | |
| Site Selection | Valley | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 1 |
| | Lake Basin | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Stack | X | X | 3 | 3 | X | X | 3 | 3 |
| Filling Scheme | Central Pond | X | X | 3 | 3 | X | X | X | X |
| | Perimeter Pond | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Containment Structures | Borrow Fill Dam | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Hydraulic Fill Dams | X | X | 3 | 3 | X | X | X | X |
| | Grout Curtains | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 |
| Mill Treatment | Additives | 1 | 1 | 3 | 3 | 1 | 1 | 3 | 3 |
| | Thickening | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Dewatering | X | X | X | X | X | X | X | X |
| Discharge Methods | Subaqueous Discharge | 2 | 2 | 3 | 3 | 2 | 2 | 3 | 3 |
| | Subaerial Discharge | 3 | 3 | 1 | 1 | 3 | 3 | 1 | 1 |
| | Thickened Discharge | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| | Conventional Disch. | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Effluent Management | Zero Decant | 1 | 1 | 1 | 1 | 3 | 3 | 3 | 3 |
| | Treat & Discharge | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Site Reclamation | Soil Cover | 3 | 3 | 1 | 1 | 2 | 2 | 1 | 1 |
| | Water Cover | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| | Vegetation | X | X | 2 | 2 | X | X | 2 | 2 |

NOTES:
1. Management methods are ranked qualitatively in accordance with the system indicated in the Legend. The ranking applies within each given set of "Canadian Conditions" and is not intended be all encompassing.
2. Long term reliability is a dominant factor in the rank of the options shown. For further details refer to discussion in the report text.

LEGEND

1. - Preferred method
2. - Adequate method
3. - Doubtful method (detailed appraisal required)
X. - Not recommended or inadequate

Consolidation and possibly dewatering are major concerns for all fine-grained wastes. Suggestions have been made to provide tailings impoundments with drains to enhance dewatering. The drainage system would require design prior to deposition of the tailings. Various options for drainage exist. Without some form of action towards drainage control, the slimes could remain untrafficable for long periods of time.

A soil cover is almost certainly required for surface impoundments. This cover should be designed to accommodate significant consolidation, as well as provide a base for vegetation. Covers could also be designed to:

- o enhance consolidation (permeable layer), and
- o inhibit oxygen migration into pyritic slimes (fine-grained, water-retaining).

The seepage emanating from the tailings over the long-term must also be addressed. Modelling studies have shown that, when the underlying materials are more permeable than the tailings, the most significant pathways for tailings porewater occurs through the underlying materials resulting in the groundwater transport of contaminants as opposed to seepage directly to the nearby surface water. Depending on the specific conditions at the site, this may or may not be a desirable process. Otherwise, seepage control will not differ significantly for slimes compared to that for whole tailings.

Special consideration must be given to sulphide-bearing uranium tailings. It was noted in Part 1 of this report that, in general, sulphide oxidation is not as significant in slimes as in coarse-grained fractions of the tailings. However, some oxidation is expected, and subsequent acid generation is likely to occur. Therefore, in sulphide-bearing tailings, measures may be required to reduce or restrict oxygen movement into the tailings, thereby alleviating significant acidification of the tailings porewater. There is evidence to suggest that certain cover designs may be appropriate for this purpose, but no evidence is available to show that engineered covers are effective for this purpose over the long-term. Studies are now in the planning stage to evaluate the effectiveness of such covers in reducing acid generation in sulphide tailings. This work is planned as part of the reactive tailings program initiated by CANMET.

It can be stated that there are no tried and true methods for long-term slimes management, especially related to uranium mill tailings. The need for management

alternatives for slimes is only currently being recognized. As suggested by D'Appolonia et al. (1972), proper abandonment of tailings facilities in general now requires planning at the design stage of the tailings facility development.

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# APPENDIX 1

## Annotated Bibliographies for Selected References

## APPENDIX I: ANNOTATED BIBLIOGRAPHIES FOR SELECTED REFERENCES

### Barbour and Krahn (1983)

Contaminant release from tailings is discussed in the context of groundwater flow. The general processes of advection, dispersion to chemical mass transfer and decay of radionuclides is considered. Numerical modelling was conducted to examine the effects of a cut-off wall beneath the tailings dyke, and the results showed that the groundwater flow velocity in the underlying materials is critical in determining contaminant transport and resulting contaminant fluxes leaving the tailings.

### Blight and Steffen (1979)

This review of South African gold mine tailings includes summaries of tailings disposal practices with an emphasis on slimes management. Much emphasis is given to the observed geotechnical properties of slimes and stability is addressed in the context of the South African environment. The dry climate allows disposal of slimes behind rather steep embankments because dewatering often occurs naturally in this semi-arid environment. It is concluded that erosion of slopes of dams by runoff is considerable and problematic. In addition, abandonment of dams is an issue that has not yet been fully addressed, and deserves further attention. It is emphasized that abandonment plans should be developed at the design stage for the tailings impoundment.

### Brawner (1979)

This paper addresses the geotechnical factors related to a construction of tailings dams. Evaluation of various factors are required before construction of these dams. These include the influence of local conditions on dam performance, such as climate, topography, geology, etc, the foundation and abutment conditions under the proposed dam, behaviour of the materials used for construction such as cycloned sand and local natural materials, construction methods, suitable design safety factor based on potential downstream problems, seepage management around and through the dam, the decant system, development of a monitoring program, as well as development of a suitable reclamation program for abandonment.

**Charlie, Doehring, Durnford and Martin (1983)**

Dewatering is discussed in the context of uranium tailings. If dewatering is conducted, bottom liners become less essential for controlling seepage, and seepage over the long-term would be greatly reduced. Seepage through the tailings both above the watertable (unsaturated) and below the watertable (saturated) are considered. It is suggested that the net flux of water through tailings that are drained, and hence unsaturated will be lower than the flux through saturated tailings. Dewatering, therefore, will minimize the potential for short- and long-term seepage, and minimize the potential for tailings liquefaction.

**D'Appolonia, Ellison and Gormley (1972)**

This review begins by noting that tailings facilities were often planned and operated to solve immediate problems of waste disposal and management of process water. Little or no consideration was often given to future abandonment of the facility. With current emphasis on safety and environmental regulations, including long-term liabilities, it is now recognized that proper abandonment requires planning at the design stage of the tailings facility development. Alternatives for the construction operation and abandonment of tailings facilities is given in terms of cash flow scenarios, indicating that the low start-up costs are more than compensated by high abandonment costs. Various disposal options are discussed, and comparisons are made between those with and without abandonment plans. The focus of the discussion is on fines from coal mining operations.

**Dean, Havens and Glanty (1974)**

This paper discusses the relative merits of stabilizing methods for fine-grainzed mineral wastes. Three modes of stabilization are noted: (1) physical that includes covering of the tailings with soil or other stabilizing materials; (2) chemical, the use of additives to interact with the fine-grained material to form crusts; and (3) vegetative to induce growth of plants on the tailings. A combination of these three approaches, such as chemical and vegetative procedures is discussed. The purpose of this process is to stablilze the tailings in addition to improving the aesthetics of the area.

**Garga, Smith and Scharer (1983)**

The key issue addressed here is pyrite oxidation leading to acid generation. The mechanisms for oxidation in tailings are discussed, and the role of oxygen, water and bacteria are included. The important geochemical reactions are given and discussed in the context of design considerations for abandonment. The importance of water on the tailings as a barrier to oxygen migration and availability on the pyrite surfaces is the major issue addressed in the consideration for tailings impoundment design.

**Grange and Cartwright (1982)**

This paper presents the experience of mine tailings management in South Africa over the past 70 years. Stabilization against wind erosion is the major concern expressed. Various stabilization methods are discussed. Re-processing of tailings has been conducted to remove significant quantities of pyritic material, and hence reduce problems of acid generation.

**Green (1980)**

This is a rather lengthy review of tailings disposal including those materials derived from metal mining operations as well as coal mining, phosphate mining, China clay production and chemical wastes that result in disposal of fine-grained materials. Standard methods of disposal are discussed. Much of the review deals with methods of dewatering and stabilization of fines (slimes), and it is noted where these methods have been used. Alternate methods of tailings disposal are presented, and include a discussion of such topics as marine disposal, underground disposal and waste reduction. Environmental considerations are addressed in terms of regulations pertaining to the disposal of tailings with a primary focus on the regulation of metal and radionuclide concentrations in mining effluents. No information has been provided on the long-term behaviour or abandonment of slimes.

**Kealy and Busch (1979)**

This is a general review of tailings disposal that includes discussion of impoundment design and construction, physical properties, sampling and testing, structural stability,

instrumentation, water management, land use planning and abandonment. In addition to many other issues, the importance of groundwater modelling for determining seepage rates and the position of the watertable within the tailings and the embankment is discussed. The influence of slime content in the tailings is shown to be important in the context of providing low hydraulic conductivities and reducing seepage. The importance of lowering the watertable or draining the tailings to reduce seepage discharge is shown. The abandonment of the tailings is considered mainly to be an issue of long-term structural stability while drainage system design and aesthetics are also considered.

**Kennedy (1978)**

Long-term stabilization of uranium tailings is discussed in the context of limiting wind and water erosion. The discussion mainly concerns arid to semi-arid environments in the U.S. where radon emanation is also problematic.

**Morell (1985)**

The impact of mine wastes on groundwater is the focus of this work. A number of sites throughout the U.S. were investigated. It was concluded that evaluating waste sources from the mining industry does not lend itself to a simple assessment of groundwater because: (1) the wastes occur over large areas; (2) the wastes are derived from natural materials in which unique or "tracer" contaminants may not exist; and (3) the waste areas may dominate the local recharge systems.

**Smith and Zyl (1983)**

The concept of dealing with the active sulphide tailings by incorporating design features into the tailings impoundments and waste rock dumps is discussed. Pyrite is noted to be the most abundant or ubiquitous form of naturally-occurring sulphides in tailings and waste rock. It is suggested that the key issues for pyrite oxidation and the subsequent production of acid in the tailings and waste rock include: (1) availability of oxygen; (2) availability of water; and (3) presence of Thiobacillus ferrooxidans ferrooxidans bacteria. Any approach to limiting the production of acid in these tailings must incorporate specific measures in the geotechnical design of the disposal facility to eliminate or reduce: (1) the inflow of groundwater or infiltration of surface waters,

including natural precipitation into the waste; (2) the availability of oxygen in the system; and (3) the activity of bacteria. It is concluded that these features must be included in the original design of the tailings impoundment.

**Volpe (1979)**

This paper discusses the material properties and structural use of copper tailings. The critical physical and engineering properties of copper tailings are identified and information from numerous case histories is displayed and discussed. Summaries of grain size characteristics, grain segregation in the tailings ponds, density, moisture contents, hydraulic conductivity, compressibility, consolidation and sheer stress are among the data presented.

**Wahler and Associates (1974)**

This review includes reference to a number of tailings operations throughout the U.S., including copper, iron, lead, zinc and phosphate operations. The main focus is on older tailings areas, many of which have not been designed for long-term stability. The major emphasis in this report is the review of maintenance and stability and the potential for failure at these various tailings sites.

**Wates (1983)**

This paper examines the consequences of dam building with slimes containing a high water content and subsequent relative low density that is usually associated with the extraction of uranium. Experience from gold mining in South Africa is discussed. It is shown how a low density reduces the practical maximum rate of rise and the associated increase in costs when conventional dams are constructed. It is considered that dewatering of slimes before position in the impoundment is the most cost-effective means of increasing the rate at which a dam can be constructed. It is concluded that, over the long-term, underground disposal seems to be a feasible alternative.

# APPENDIX 2

## Summary of Questionnaire Responses

## APPENDIX 2: SUMMARY OF QUESTIONNAIRE RESPONSES

A total of eight responses were received from the questionnaire sent to mines or mining companies. One-half of the respondents were from Canada, two from the U.S.A., one from Ireland, and one from Australia. The Canadian mines extracted gold, silver and/or copper; the U.S. mines extracted phosphate and electrum; the Irish mine was a lead/zinc mine; and the Australian mine was a uranium property. All of the properties are active. A summary of the responses is given in Tables A2.1 through A2.10. Typed copies of the actual responses are presented in a separate volume.

The storage methods varied considerably with three of the respondents using perimeter dykes and conventional stacking techniques; two of the respondents making use of local topography and using valley deposition; one respondent using lake (shallow water) deposition; one respondent using thickened conical discharge; and one respondent using abandoned underground mine workings. The shallow lake storage system (Australia) will eventually change to a conventional stack using perimeter dykes. Only one of the tailins basins used special densification methods (well points at the mine in Quebec). Two of the properties separated the coarse fraction tailings for backfill by cycloning.

Six of the eight respondents reported recirculation from a tailings or polishing pond ranging from 35 to 100% of effluent discharge to tailings area. Four of the eight responses indicate some form of water treatment is required during operation, including pH control, cyanide degradation and heavy metal precipitation.

Only one of the eight respondents (Australia) indicated they had a decommissioning plan. Four others indicated that some decommissioning was planned, but that details were not yet available. The response from the Australian uranium mine indicated the decommissioning process would include removal of ponded water, flattening of dam slopes, grouted foundations, and a surface treatment consisting of a granular base, clay cover and vegetation. Two other respondents mentioned the plan to provide the tailings with either a soil or vegetation cover.

Five responses indicated that groundwater and/or surface water quality was being monitored at variable frequencies during operation. Only one response indicated any plan for monitoring following decommissioning. The ongoing monitoring programs varied

considerably from ten wells sampled infrequently to up to 50 sampling stations sampled monthly.

Only four respondents indicated any post-decommissioning concerns and, of those who provided any details, erosion, dust and surface water contmination were cited as long-term concerns.

TABLE A2.1: GENERAL INFORMATION

| Company/ Mine | Climate | Minerals Extracted | Extraction Process | Status of Tailings Area |
|---|---|---|---|---|
| 1 | Subtropical | Uranium as pitchblende | Acid leach | Active |
| 2 | Temperate | Gold and silver | Cyanidation Leach | Active |
| 3 | Temperate | Zinc and lead | Flotation | Active |
| 4 | Subtropical | Phosphate | Hydrocyclone, flotation | Varies from active to decommissioned |
| 5 | Subarctic | Chalcopyrite, sphalerite, galena | Flotation | Active |
| 6 | Temperate/ Subarctic | Gold | Cyanidation leach | Active |
| 7 | Arid | Electrum | Gravity separation/ flotation | Active |
| 8 | Arid/ Subarctic | Copper, gold, silver | Flotation | Active |

Location Code

1 = Australia
2 = Quebec
3 = Ireland
4 = Florida
5 = Ontario
6 = Ontario
7 = Nevada
8 = Quebec

TABLE A2.2: OPERATIONAL DATA

| Company/ Mine | Operating Life (years) | Production Rate (tonne/day) | Storage Scheme | Slurry Density (% solids) | Depositional Method | Slope of Beach (%) | Densification Method |
|---|---|---|---|---|---|---|---|
| 1 | o 6 to date<br>o 12 total | 3,500 | shallow water (lake) | 35 | end dumping | not known | none used |
| 2 | o 3.5 years to date<br>o 4.5 years total | 400 | underground in old mine workings | 40 | dumping in open stope 880 ft deep | N/A | none used |
| 3 | o 10 years to date<br>o 12 years total | 3,000 | stack | 15 | end dumping | 1 | none used |
| 4 | o 2 to 3 years per cell | N/R | perimeter dykes or abandoned pit | 5 | N/R | N/R | surficial dessication |
| 5 | o 20 years to date<br>o 50 years total | 9,200 | thickened conical discharge | 16-18 | spigotting | 1.6 | on-site thickeners |
| 6 | o 2 years to date<br>o 25 years total | 2,100 total<br>700 to backfill | valley deposition<br>mine backfill | 25-30 | end dumping<br>cycloning for mine backfill | 0.5 | none used |
| 7 | o 3 years to date<br>o 6 years total | 1,275 | valley deposition | N/R | spigotting | 1 | none used |
| 8 | 35 years total | 600 | stack<br>mine backfill | N/R | end dumping<br>cycloning for backfill | not known | well points |

N/A - not applicable.
N/R - no response.

TABLE A2.3: BASIN CHARACTERISTICS

| Company/ Mine | Watershed Area (ha) | Area Diverted (ha) | Tailings Area (ha) | Ponded Area (%) | Foundation Conditions | Siesmicity |
|---|---|---|---|---|---|---|
| 1 | 100 | none | 100 | 100 (at present) | 2 m laterite gneiss bedrock | low |
| 2 | N/A | N/A | N/A | N/A | N/A | N/R |
| 3 | 75 | none | 75 | 60 | 3 m of glacial till | low |
| 4 | 0 | none | 81 per cell | 90 | 12-20 m of sand over limestone | low |
| 5 | N/R | 1,215 | 1,215 | 25 | 1-3 m of muskeg | low |
| 6 | 243 | 8 | 162 | 40 | 0-3 m muskeg over clay | low |
| 7 | 61 | none | 14 | 5 | 1 m weathered limestone amd limestone | high |
| 8 | N/R | N/R | N/R | N/R | 6-12 m gravel | N/R |

TABLE A2.4: TAILINGS/EFFLUENT CHARACTERISTICS

| Company/ Mine | Tailings Gradation | Specific Gravity | Dry Density ($T/m^3$) | Acid Potential | Effluent pH | Major Elements in Effluent |
|---|---|---|---|---|---|---|
| 1 | o 59% 200 mesh (0.08 mm)<br>o 42% 400 mesh (0.04 mm) | 2.8 | 0.86 | low | o at mill 7-7.5<br>o at decant 5.5-6.5 | $SO_4$, Mn, Mg, U, $NO_3$, Ra-226, Ca |
| 2 | 100% 200 mesh (0.08 mm) | 2.8 | N/R | N/R | o at mill 10.5<br>o at discharge 9.5 | Cu, Cd, Zn, K, Ni, Fe, Co |
| 3 | 95% 200 mesh (0.08 mm) | 2.9 | N/R | low | o at mill 9.5<br>o at decant 8.5 | Zn, Fe, Pb, Cu, Cd |
| 4 | o 20% 0.04 mm<br>o 80% 0.004 mm | 2.7 | - | N/R | N/R | N/R |
| 5 | o 95% 200 mesh (0.08 mm)<br>o 80% 400 mesh (0.04 mm) | 3.0 | 1.6 | N/R | at mill 9.0 | Zn, Fe, S, Cu, Pb |
| 6 | 99% 200 mesh (0.08 mm) | 2.8 | - | low | o at mill 10.5<br>o at decant 7.9 | CN, Zn, Cu, N, Pb |
| 7 | 72% 200 mesh (0.08 mm) | 2.65 | - | none | 7.0 | Si, TOC, Cl, CN, N, P, F |
| 8 | N/R | 3.2 | - | none | o at mill 9.5<br>o at decant 8.4 | Cu, As, Zn, Fe, Pb |

N/R - no response.

TABLE A2.5: CHARACTERISTICS OF CONTAINMENT STRUCTURES

| Company/ Mine | Type of Dams/Dykes | Method of Raising | Foundation Conditions |
|---|---|---|---|
| 1 | Perimeter waste, rock dykes (in future) | Downstream in stages (in future) | Not known |
| 2 | None | None | None |
| 3 | Low permeability perimeter dams | Perimeter dams built to final elevation | Glacial till |
| 4 | Permeable perimeter dams | Perimeter dams built to final elevation | Granular soil |
| 5 | Low permeability perimeter dykes | Not specified | N/R |
| 6 | Imported fill, low permeability, zoned embankment | N/R | Clay over rock |
| 7 | Waste rock embankment | N/R | Bedrock |
| 8 | N/R | N/R | N/R |

N/R - no response.

TABLE 2.6: WATER MANAGEMENT DATA

| Company/ Mine | Average Annual Precipitation (mm) | Effluent Discharge ($m^3$/day) | Recirculation (%) | Evaporation Annual (mm) | Flood Control Measures |
|---|---|---|---|---|---|
| 1 | 1,560 | N/R | 75 | 1,950 (est) | 4 m freeboard at start of wet season |
| 2 | Not known | 550 | 41 | Not known | None |
| 3 | 830 | 28,380 | 100 | 500 (est) | None required |
| 4 | 1,140 | N/R | 100 | 1,140 (est) | N/R |
| 5 | 900 | 76,320 | 35 | 50 (est) | Emergency spillways |
| 6 | 838 | 10,355 | 0 | Unknown | Wier at overflow |
| 7 | 2,500 | 3,270 | 66 | Unknown | 1.5 m freeboard on dam |
| 8 | N/R | N/R | 0 | Unknown | N/R |

N/R - no response.

TABLE A2.7: TREATMENT

| Company/ Mine | Treatment Requirements | Treatment Process | Effluent Collection | Precipitate Management |
|---|---|---|---|---|
| 1 | pH modification in tailings | Hydrated lime in tailings | N/R | None |
| 2 | Cyanide degradation and copper precipitation | Sodium sulphate | Polishing pond | Settling Pond 5 |
| 3 | None | None | N/A | N/A |
| 4 | N/R | N/R | N/R | N/R |
| 5 | Treatment for heavy metals | Lime addition | Perimeter drains | Precipitation in 105 ha settling pond |
| 6 | Cyanide and heavy metals control | Impoundment | Sedimentation pond | Settling pond |
| 7 | None | None | N/R | N/R |
| 8 | None | None | None | None |

N/A - not applicable.
N/R - no response.

TABLE A2.8: DECOMMISSIONING PROCESS

| Company/ Mine | Status | Drainage | Flood Control | Containment Structures | Surface Treatment |
|---|---|---|---|---|---|
| 1 | Planned but not implemented | o remove ponded water<br>o evaporation | None required | o flatten slopes<br>o construct berms<br>o grout foundations | o granular base<br>o clay cover<br>o vegetation |
| 2 | Planned but no details | N/R | N/R | N/A | N/A |
| 3 | Not planned | N/R | N/R | N/R | N/R |
| 4 | N/R | N/R | N/R | N/R | N/R |
| 5 | Planned but no details | N/R | N/R | N/R | N/R |
| 6 | Planned but no details | N/R | N/R | N/R | vegetation |
| 7 | Planned but no details | N/R | N/R | N/R | Clayey soil cover |
| 8 | N/R | N/R | none | none | none |

TABLE A2.9: MONITORING PLAN

| Company/ Mine | Status | Instrumentation | Schedule | Inspection Frequency | Surface Water | Groundwater | Air |
|---|---|---|---|---|---|---|---|
| 1 | o current<br>o planned following closeout | o piezometers<br>o settlement gauges<br>o slope indicators | 10 years following closeout | o daily during operation<br>o event related for 10 years | 50 stations sampled monthly | 46 stations sampled monthly | o dust<br>o radon<br>o gamma |
| 2 | current | none | N/R | twice weekly | 3 stations sampled twice weekly | N/R | N/R |
| 3 | current | piezometers | during operation | monthly during operation | N/R | 10 wells around dykes monitored infrequently | dust |
| 4 | no monitoring planned | N/A | N/A | N/A | N/A | N/A | N/A |
| 5 | current | o piezometers<br>o settlement gauges<br>o slope indicators | during operation | monthly during operation | 8 stations sampled daily | N/R | N/R |
| 6 | current | none | none | semi-annual during operation | 2 stations monitored weekly | N/R | N/R |
| 7 | no monitoring planned | none | none | N/R | none | 2 stations monitored yearly | none |
| 8 | no monitoring planned | N/R | N/R | N/R | N/R | N/R | N/R |

TABLE A2.10: POST-DECOMMISSIONING CONCERNS

| Company/ Mine | Status | Description |
|---|---|---|
| 1 | Anticipated concerns | o erosion approaching natural rates<br>o surface drainage controlled by diversions, structures and ponds<br>o minimal groundwater contamination<br>o radon emissions close to background |
| 2 | N/R | N/R |
| 3 | Anticipated concerns | N/R |
| 4 | N/R | N/R |
| 5 | Anticipated concerns | o wind erosion<br>o potential dust problem |
| 6 | Anticipated concerns | contamination of natural streams |
| 7 | No concerns | N/R |
| 8 | N/R | N/R |